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Aerobic and skeletal muscle architectural adaptations to concurrent marathon and circuit resistance training

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Aerobic and Skeletal Muscle Architectural Adaptations to Concurrent Marathon and
Circuit Resistance Training

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A thesis submitted to the Graduate Faculty of

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ABSTRACT

Purpose: The purpose of this investigation was to examine performance-related physiological adaptations ($\text{VO}_{2\text{max}}$, Lactate Threshold, and Running Economy) and skeletal muscle architectural changes (muscle thickness, pennation angle, and fascicle length) of the vastus lateralis (VL) and lateral gastrocnemius (LG) to marathon training with and without a concurrent circuit resistance-training program. **Methods:** Thirteen subjects (21 ± 1 yrs, 171 ± 2 cm, 65 ± 2 kg, 55 ± 2 ml/kg/min) completed a 15-week progressive marathon-training program. Nine subjects completed the 15 weeks of progressive marathon-training alone (AE), while 4 subjects participated in the 9-week circuit training program (CONC), in addition to the run training. $\text{VO}_{2\text{max}}$, lactate threshold, running economy, muscle thickness, pennation angle and fascicle length were assessed before and after training. 2x2 repeated measures ANOVAs and Wilcoxon Signed-Rank Tests were used to test the effects of the concurrent training intervention (AE vs. CONC) and general training program (pre vs. post training). Pearson correlations were utilized to examine relationships between changes in architectural and cardiovascular/metabolic parameters. **Results:** Absolute $\text{VO}_{2\text{max}}$ (L/min) increased in ALL with training (3.58 ± 0.18 vs. 3.73 ± 0.22 ; $p=0.018$), with a 9% increase in CONC (3.52 ± 0.38 L/min vs. 3.87 ± 0.50 L/min; $p=0.031$) and no change in AE. Lactate threshold increased significantly in ALL post-training (12.4 ± 0.3 kph vs. 13.2 ± 0.3 kph; $p=0.012$), with no differences between groups. There were no changes in running economy [submax VO_2 (ml/kg/min)]. LG pennation angle increased in ALL ($17 \pm 1.0^\circ$; $p=0.056$), with no differences between groups, while VL pennation angle did not change.

There were no changes in muscle thickness or fascicle length in the VL or LG.

Conclusion: Notwithstanding the small sample size, concurrent marathon and circuit training appears to increase absolute $\text{VO}_{2\text{max}}$ to a greater extent than marathon training alone. Marathon training increases LG pennation angle, and the change is not influenced by concurrent circuit resistance training. These findings suggest that that it can be beneficial for beginning marathon runners to supplement with concurrent circuit training programs, and that LG pennation angle is highly sensitive to endurance run training.

CHAPTER ONE

INTRODUCTION

Marathon running has grown in popularity over the past few decades, with nearly half a million individuals completing the marathon distance (42.2 km) in the U.S. in 2009 (45). Because resistance exercise elicits increases in strength and resting metabolic rate (2, 3, 5, 18, 31, 55), marathon run-training programs are commonly complimented with some form of resistance training (concurrent resistance and aerobic exercise training). Circuit style resistance training programs employ total body routines with high repetitions and short recovery intervals between exercises. The impact of adding a circuit resistance-training program to an existing marathon program on global physiological adaptations (cardiovascular, metabolic, and muscular) is largely unknown. The primary objective of the current project is to examine performance-related physiological adaptations and skeletal muscle architectural changes to marathon training with and without a concurrent circuit resistance training program.

Endurance running performance is determined by a number of physiological attributes. The following three factors, in particular, appear to play an integral role in distance running performance potential: maximal oxygen consumption ($\text{VO}_{2\text{max}}$), lactate threshold and running economy. Each of these variables can be altered with repeated sessions of endurance exercise (7, 11, 14, 17, 48, 50, 52, 54, 57). The extent that these variables are altered with training is dependent upon prior fitness level, duration and intensity of the program, duration and intensity of the individual training sessions, and genetic predisposition (10, 59). Conventional resistance training has no effect on the

primary physiological determinants of endurance performance (1, 8, 24, 42), while circuit training elicits aerobic adaptations (16, 23, 31, 40, 62), especially in *untrained* individuals. Whether concurrent circuit training enhances these adaptations when compared to run training is unknown.

$\text{VO}_{2\text{max}}$ represents an individual's peak rate of aerobic energy expenditure and is associated with endurance performance (48). Genetic predisposition accounts for nearly half of the differences in $\text{VO}_{2\text{max}}$ between individuals (10). Aerobic training, such as run training, increases $\text{VO}_{2\text{max}}$ by increasing maximal cardiac stroke volume and arterial-venous oxygen differential (54, 55). Gains in $\text{VO}_{2\text{max}}$ are not likely to occur in response to most forms of traditional resistance training (11, 22, 25, 26, 37), as traditional resistance exercise does not deliver a sufficient aerobic stimulus (11). Traditional resistance training programs use routines that involve progressive 8-12 repetition sets with 1-3 minutes of rest between sets. However, circuit training, is characterized by high-repetition (15-20+) sets with minimal rest periods, and does appear to improve $\text{VO}_{2\text{max}}$ (16, 23, 31, 40, 62). $\text{VO}_{2\text{max}}$ is not enhanced when resistance exercise is added to an established aerobic training program in *endurance-trained* individuals, while it does not appear to hinder $\text{VO}_{2\text{max}}$ (1, 8, 24, 42). The only study to examine the effect of concurrent traditional resistance training on $\text{VO}_{2\text{max}}$ in recreational marathon runners reported null findings (17). The effects of adding circuit-training to an established aerobic training program are unknown. Recreational runners could benefit from the added training volume and aerobic stimulus that circuit resistance-training programs provide, when adding additional running to the training program may not be plausible (i.e. orthopedic injury risk).

Lactate threshold is the point at which blood lactate levels rise exponentially during incremental exercise. Lactate threshold influences distance running performance because it partially determines the proportion of $\text{VO}_{2\text{max}}$ that can be sustained before lactate production exceeds lactate removal (i.e. highest sustainable running speed). Once the threshold is exceeded, intensity must decrease before fatigue and cessation of exercise become imminent. Very little is known about the impact of concurrent circuit training on lactate threshold. Marcinik and colleagues observed a 12% increase in lactate threshold in untrained individuals following 12-weeks of circuit training, as well as decreased lactate levels at a given submaximal intensity (40). Similarly, lactate threshold improved by 15% in a group of recreationally active females who commenced circuit-like resistance training for 5 weeks (16). Adding traditional resistance training to beginning marathon run training does not appear to alter lactate threshold (17). However, the potential exists for concurrent circuit training to enhance the adaptation.

Running economy is the oxygen requirement at a given running speed or velocity ($\downarrow \text{O}_2 = \uparrow$ economy). The addition of resistance training to an established run training program has been shown to improve running economy in several studies. Specifically, resistance training (3 x week) improved running economy in trained female cross-country runners by 4% (29). Further, 6-9 weeks of plyometrics and high velocity resistance training improved running economy by as much as 8.1% in trained distance runners (46, 50). These improvements in running economy are functionally relevant and clearly beneficial over long distances such as the marathon. Concurrent traditional resistance training in novice marathon runners produced no significant change in running economy

(17). The effect of concurrent circuit training on running economy in recreational marathon runners is largely unknown.

Unlike the primary determinants of running performance, the impact of aerobic training on skeletal muscle architecture is not well understood. Human skeletal muscle function and consequently whole body function is potentially influenced by muscle architecture (form = function) (44). Human skeletal muscle architecture is defined by several interrelated parameters including muscle thickness (size: the distance between the superficial and deep borders of a muscle), pennation angle (the angle at which muscle fibers are oriented between each tendon), and fascicle length (the length of bundled muscle fibers in series between each tendon) (44). Generally, muscles of long fascicle length contract more quickly yet lack strength due to obligatory compromises in muscle thickness. Resistance training alters all parameters of muscle architecture in a fashion that is likely to improve whole muscle function (3, 7, 9, 32, 52, 56). Significant changes in muscle thickness, pennation angle, and fascicle length have been noted as early as 3 weeks into a progressive resistance exercise program (52). Further, sprinters have thicker musculature, smaller pennation angles and longer fascicles than endurance runners (4). Indeed, our laboratory recently observed marked architectural changes in the lateral gastrocnemius (calf) with marathon run training (Murach and Luden, unpublished observations). Architectural adaptations may support the ability to continuously run 42.2 km (26.2 miles). However, whether these adaptations are influenced by any form of concurrent resistance exercise is unknown.

Circuit training has the potential to elicit increases in $\text{VO}_{2\text{max}}$ and markedly alter lactate threshold in *untrained* individuals (16, 23, 31, 40, 62). Very little is known about

the effects of concurrent circuit training on lactate threshold adaptations to distance run training. It is currently undocumented how running economy in an untrained population would be affected by concurrent circuit training. Noting that untrained individuals seem to be more sensitive to additional training loads, resistance training may have greater impact on $\text{VO}_{2\text{max}}$, lactate threshold and running economy in an untrained or recreationally active population compared to trained runners. Alterations in skeletal muscle architecture in response to short-term concurrent training are largely unknown. To our knowledge this is the first study to examine the effect of marathon training with and without concurrent circuit training on cardiorespiratory, metabolic and skeletal muscle architectural adaptations in a young, recreationally active population.

Aims and Hypotheses

Aim 1- To determine if marathon training with concurrent circuit training influences $\text{VO}_{2\text{max}}$ differently than marathon training alone.

Hypothesis 1- Marathon training with concurrent circuit training will influence $\text{VO}_{2\text{max}}$ differently than marathon training alone.

Aim 2- To determine if marathon training with concurrent circuit training influences lactate threshold differently than marathon training alone.

Hypothesis 2- Marathon training with concurrent circuit training will influence lactate threshold differently than marathon training alone.

Aim 3- To determine if marathon training with concurrent circuit training will influence running economy differently than marathon training alone.

Hypothesis 3- Marathon training with concurrent circuit training will influence running economy differently than marathon training alone.

Aim 4- To determine if marathon training with concurrent circuit training will influence skeletal muscle architecture (thickness, pennation angle, and fascicle length) in the vastus lateralis and gastrocnemius differently than marathon training alone.

Hypothesis 4- Marathon training with concurrent circuit training will influence skeletal muscle architecture of the vastus lateralis and gastrocnemius differently than marathon training alone.

Significance of the Study

To date, only one study has examined the effects of concurrent training on the major physiological determinants of endurance performance ($\text{VO}_{2\text{max}}$, lactate threshold, and running economy) in recreational marathon runners, and there were no additional increases observed with the addition of traditional resistance training (17). The investigators did not examine the effect of whole body circuit training, which has been shown to improve $\text{VO}_{2\text{max}}$ and lactate threshold in other populations. Changes in skeletal muscle architecture in response to training have the potential to support endurance performance. This is the first study to examine concurrent training's effect on the primary physiological determinants of endurance performance and skeletal muscle architectural changes

CHAPTER TWO

REVIEW OF THE LITERATURE

Objectives

The objectives of this chapter are to provide an overview of: 1) cardiovascular and metabolic adaptations to resistance training, 2) cardiovascular and metabolic adaptations to aerobic training, 3) cardiovascular and metabolic adaptations to concurrent training and 4) skeletal muscle architectural adaptations to aerobic and resistance training.

Physiological Determinants of Endurance Performance

By most accounts, the 3 primary physiological determinants of endurance performance are $\text{VO}_{2\text{max}}$, lactate threshold, and movement economy. $\text{VO}_{2\text{max}}$ represents an individual's peak rate of aerobic energy expenditure. While not a direct predictor of performance, elite endurance athletes typically have high aerobic capacities. Lactate threshold is the point at which blood lactate levels rise exponentially during incremental exercise. A runner with a high lactate threshold can run at a higher percentage of $\text{VO}_{2\text{max}}$ before the rate of lactate production exceeds the rate of lactate removal, which can lead to fatigue (reduced intensity or cessation of exercise). Movement economy is the oxygen requirement of any given exercise intensity ($\downarrow \text{O}_2 = \uparrow \text{economy}$). Improvements in economy permit a runner to maintain a high running velocity (12). It is well documented that each of these parameters has the potential to improve as a result of aerobic training.

Cardiovascular and Metabolic Adaptations to Aerobic Training

$\text{VO}_{2\text{max}}$ improves following repeated bouts of aerobic exercise, and is mediated through gains in maximum cardiac output and maximum arterial-venous oxygen differential (i.e. oxygen extraction) (7, 12, 15, 18, 38, 49, 52, 55, 58, 61). A seminal study by Saltin et al. demonstrated that, 42 men (mean age = 40.5 years) who ran approximately 2 miles, 3 days per week over an 8-10 week period increased their absolute $\text{VO}_{2\text{max}}$ increased from 2.89 L/min to 3.44 L/min (49). Similar improvements in relative $\text{VO}_{2\text{max}}$ have been noted following 12-24 minutes of jogging for 10 weeks (61). Modest beginning marathon training (13 weeks, 15-36 miles per week), yielded a 10% increase in relative $\text{VO}_{2\text{max}}$ (38). These data suggest that aerobic training increases $\text{VO}_{2\text{max}}$ in *untrained individuals* and improvement can be observed in short periods of time with relatively low training volumes.

Aerobic training can improve lactate threshold in untrained or recreationally active individuals (12, 15, 49, 53). Saltin et al. reported lower blood lactate concentrations at fixed submaximal oxygen uptake rates after a 6-mile per week training program in untrained males (49). Similar to what has been observed with $\text{VO}_{2\text{max}}$, the most marked reductions in lactate concentrations after training were observed in the individuals that started with the lowest fitness levels. The literature has evolved to indicate that improvements in lactate threshold are consistently observed with varying intensities and modalities. Modest cycling programs (9 weeks, 4 days per week) (14), running programs (6-8 weeks, 20-30 minutes at 60-70% $\text{VO}_{2\text{max}}$) (7, 12), and the addition

of interval training or high intensity runs at velocities above lactate threshold (53) elicit 4-15% improvements in lactate threshold. Clearly, lactate threshold improves following repeated prolonged bouts of aerobic training, and the adaptation is marked in individuals with lower fitness levels.

Although there was no reported improvement in running economy following a 9-week cycling program (which lacks specificity to running adaptation) (15), 6-8 weeks steady-state and interval run training has been shown to improve running economy by as much as 8% (7, 18). In regards to beginning marathon training, running economy improved by 7% following a 13-week marathon-training program (38). Scrimgeour et al. divided thirty male distance runners into three groups of ten according to their weekly training volume. An examination of running speeds at a given percentage of VO_{2max} revealed that runners training more than 100 km/week had significantly faster running speeds at submaximal intensities, and therefore significantly higher (20%) running economies, thereby suggesting that running economy improves with higher volumes of aerobic training, or that economical adaptation supports tolerance of higher training volumes (41). The state of the literature suggests that aerobic training improves running economy and that higher training volumes can potentially yield greater improvements.

Improvements in VO_{2max} , lactate threshold and running economy have all been demonstrated in response to aerobic training (7, 10, 11, 14, 17, 35, 37, 39, 48, 52, 54, 57, 60). Interestingly, it appears that both VO_{2max} and lactate threshold can be improved by running as little as 6 miles per week in previously sedentary individuals (48). Runners who train at higher volumes (more than 100 km per week) tend to be more economical at given running speeds than those with lower training volumes (40). Both VO_{2max} and

running economy have the potential to improve in response to beginning marathon training, while less is known about the effects on lactate threshold (38, 58).

Table 2.1 – Cardiovascular and Metabolic Adaptations to Aerobic Training

Author	Subjects	Workload	Duration	VO_{2max}	LT	RE
Saltin 1962 (49)	42 untrained men	2 miles	3 d/wk 8-10 wks	↑ 19%	↑	NA
Wilmore 1970 (61)	55 men between ages 17-59	12/24 minutes of jogging	3 d/wk 10 wks	12 min ↑ 6% 24 min ↑ 10%	NA	NA
Davis 1979 (15)	9 sedentary middle-aged males	45 min cycling 50-70% HRR	4 d/wk 9 wks	↑ 29%	↑ 15%	↔
Sjodin 1982 (53)	8 trained distance runners	Added a 20 minute run at OBLA to regular training	1 day/wk 14 wks	↔	↑ 4%	NA
Scrimgeour 1986 (51)	30 distance runners	>60 km/wk 60-100 km/wk 100+ km/wk	NA	NA	NA	100+km/wk ↑20%
Spina 1992 (55)	6 healthy men and women	40 min running + interval training	3 d/wk running 3 d/wk interval training	↑19%	NA	NA
Billat 1997 (7)	8 endurance trained males	40 min 60-70% VO _{2max} or 40 min interval	6 d/wk 8 wks	↔	↔	↑8%
Franch 1998 (18)	36 recreational runners	20-30 min running	3 d/wk 6 wks	↑6%	NA	↑3%
Carter 1999 (12)	16 sport science students	20-30 min running	3-5 d/wk 6 wks	↑9%	↑6%	NA
Trappe 2006 (58)	7 recreational runners	15-36 miles of running/wk	4 d/wk 13 wks	↔	NA	↑7%
Luden 2011(38)	6 recreational runners	15-36 miles of running/wk	4 d/wk 13 wks	↑10%	NA	↔

LT= Lactate Threshold RE= Running Economy, km= kilometers

Cardiovascular and Metabolic Adaptations to Resistance Training

Traditional resistance training programs use routines that involve progressive 8-12 repetition sets with 1-3 minutes of rest between sets. $\text{VO}_{2\text{max}}$ is largely unaffected by traditional resistance training alone (11, 22, 25, 35, 37, 40). For example, Hickson et al. reported a 4% increase in absolute, but no increase in relative $\text{VO}_{2\text{max}}$ in response to a 10-week quadriceps resistance training program (25). Kraemer observed no increase in relative $\text{VO}_{2\text{max}}$ following a 12-week, traditional total-body routine (35). Likewise, Goreham et al. reported that relative $\text{VO}_{2\text{max}}$ did not change with a 12-week traditional lower-body resistance program (22). Additionally, an 8-week low repetition (3-5 RM), intermediate repetition (9-11 RM), and high repetition (20-28 RM) lower body resistance training programs all failed to alter $\text{VO}_{2\text{max}}$ (11). Collectively, these data indicate that increases in $\text{VO}_{2\text{max}}$ are not likely following programs characterized by traditional set/rep breakdowns with ample rest periods (1-3 minutes).

While findings in the literature have not been consistent, circuit training, which is characterized by 15-20+ repetitions with minimal rest periods (> 1 minute), has the potential to increase $\text{VO}_{2\text{max}}$. In several instances prolonged (12-20 weeks) circuit training in untrained individuals failed to alter relative $\text{VO}_{2\text{max}}$ (19, 20, 40). However, Wilmore et al. and Haenell et al. reported an 11% and 12% increase in absolute and relative $\text{VO}_{2\text{max}}$ following similar 9 and 10-week circuit training programs, respectively (23, 62). At least two investigations directly compared the magnitude of cardiovascular adaptations between circuit and endurance training, and the findings are mixed. Gettman et al. found that endurance-training yielded a 14.5% higher increase in relative $\text{VO}_{2\text{max}}$ than circuit training (19). However, 12 weeks circuit-training and 12 weeks of

endurance-training group both elicited 11-12% improvements in relative and absolute $\text{VO}_{2\text{max}}$ (24). These data suggest that high repetition resistance protocols with limited rest between sets have the potential to increase $\text{VO}_{2\text{max}}$.

In *untrained individuals*, high-intensity, low-rest resistance protocols have the potential to increase lactate threshold, as demonstrated by both Marcinik and Edge (16, 40). Marcinik et al. examined the effects of a 12-week high-repetition (8-20 RM) low rest (30 seconds) total body resistance training program on cardiovascular and metabolic adaptations and reported a 12% increase in lactate threshold versus controls (40). Recently, Edge et al. performed a similar 5-week protocol among recreationally active females and noted a marked improvement (15%) in lactate threshold with training (16). Conversely, lactate threshold was not altered with 8-weeks of low repetition (3-5 RM), intermediate repetition (9-11 RM), or high repetition (20-28 RM) lower body resistance-training (11). The body of literature is limited, however it appears that circuit training has the potential to increase lactate threshold.

Collectively, $\text{VO}_{2\text{max}}$ is largely unaffected by traditional resistance training alone (11, 22, 25, 35, 37, 40). While less obvious (19, 20), circuit training has the potential to increase $\text{VO}_{2\text{max}}$ (22,23,60). Traditional resistance training programs performed on their own are unlikely to impact lactate threshold (11), whereas circuit resistance training programs can positively influence lactate threshold (16, 40). Finally, nothing is known about the effects of any form of resistance training alone on running economy.

Table 2.2 – Cardiovascular and Metabolic Adaptations to Resistance Training

Author	Subjects	Workload	Style	Duration	VO₂max	LT
Wilmore 1978 (62)	28 untrained men and Women	3 sets of max reps in 30 sec at 40-55% 1RM with 15 seconds rest	Circuit	10 wks 3 d/wk	Women ↑10.7% Men ↔	NA
Gettman 1978 (19)	27 men CWT (n=11) END (n=16)	2 sets of 15 reps with 20-25 sec rest	Circuit	20 wks 3 d/wk	END↑14.5% CWT ↔	NA
Hickson 1980 (25)	9 untrained men	Heavy quad resistance training	Traditional	10 wks 5 d/wk	↑ 4%	NA
Gettman 1982 (20)	36 females 41 males	3 sets of 12-15 reps with 15 seconds rest total body	Circuit	12 wks 3 d/wk	↔	NA
Haennel 1989(23)	32 healthy middle-aged men	3 sets max reps in 20 sec intervals 20 sec rest total body	Traditional	9 wks 3 d/wk	↑12%	NA
Marcinik 1991 (40)	18 untrained males S (n=10) CON (n=8)	3 sets of 8-20 RM. 30 sec rest total-body	Circuit	12 wks 3 d/wk	↔	↑12%
Kraemer 1995 (35)	9 healthy men	2-5 sets of 5-10 RM total body	Traditional	12 wks 4 d/wk	↔	NA
Goreham 1999 (22)	7 untrained males	3 sets of 6-8 RM lower-body	Traditional	12 wks 3 d/wk	↔	NA
Kaikkonen 2000 (31)	90 sedentary adults CWT (n=27) END(n=29) CON (n=27)	3 sets of max reps (40 sec) 20 seconds rest total-body	Circuit	12 wks 3 d/wk	CWT ↑ 11% END ↑ 12%	NA
Lemura 2000 (37)	12 sedentary women	2 sets of 8-10 reps at 60-70% 1 RM total-body	Traditional	16 wks 3 d/wk	↔	NA

END= Endurance training only CWT= Circuit Weight Training S= Traditional Strength Training LR= Low Rep, High Resistance IR= Intermediate Rep. Intermediate Resistance HR= High Rep. Low Resistance CON= Control

Table 2.2 – Cardiovascular and Metabolic Adaptations to Resistance Training continued.

Author	Subjects	Workload	Style	Duration	VO_{2max}	LT
Campos 2002 (11)	32 untrained men LR (n=9) IR (n=11) HR (n=7) CON(n=5)	LR= 3-5 RM IR=9-11 RM HR=20-28 RM 1-3 min rest lower-body	Traditional	8 wks 2-3 d/wk	↔	↔
Edge 2006 (16)	16 recreationally active females	3-5 sets of 15-20 reps total body	Circuit	5 wks 2-3 d/wk	↔	↑15%

END= Endurance training only CWT= Circuit Weight Training S= Traditional Strength Training LR= Low Rep, High Resistance IR= Intermediate Rep, Intermediate Resistance HR= High Rep, Low Resistance CON= Control

Cardiovascular and Metabolic Adaptations to Concurrent Training

Concurrent training programs incorporate both aerobic and resistance training. Many aerobic training programs include resistance training, perhaps because it increases both muscular strength and resting metabolic rate (14, 34). While not compromised, $\text{VO}_{2\text{max}}$ and lactate threshold are largely unaffected by concurrent traditional resistance training in *endurance-athletes* (8, 17, 20, 24, 26, 29, 41, 42, 43, 46, 50, 59). However, there is very little data on cardiovascular and metabolic adaptations, with the exception of $\text{VO}_{2\text{max}}$, to concurrent training in *untrained* or *recreationally active* individuals.

An increase in $\text{VO}_{2\text{max}}$ is likely to occur as a result of aerobic training (7, 11, 14, 17, 37, 48, 52, 54, 57, 60) and in response to circuit training (23, 24, 62). However, no form of concurrent resistance exercise has been shown to enhance $\text{VO}_{2\text{max}}$ to a greater extent than aerobic training alone. McCarthy et al. compared the response to a traditional resistance training program, cycle training, and a combination of the two in an untrained population. The concurrent training group experienced similar gains in $\text{VO}_{2\text{max}}$ compared to the cycling group (40). Similar results were noted following 20 weeks of concurrent run and circuit training in untrained individuals (20). In endurance trained populations it is well documented across a number of studies that there is no further increase in $\text{VO}_{2\text{max}}$ when resistance training is added to an established aerobic training program (8, 24, 26, 29, 44, 45, 47, 51, 60). However, only one study to date has examined the effect of concurrent conventional resistance training on $\text{VO}_{2\text{max}}$ in recreational marathon runners. Ferrauti and colleagues added an 8-week traditional lower body resistance training program to the regimen of recreational marathon runners and there were no differences in $\text{VO}_{2\text{max}}$ between concurrent and aerobic training groups following the intervention (17). They did not examine the effects of circuit training, which improves $\text{VO}_{2\text{max}}$ (23, 24, 62).

No data has been gathered on the effects of concurrent traditional or circuit resistance training on lactate threshold. Both Paavolanien and Saunders examined the effects of concurrent plyometric training on lactate threshold in endurance-trained populations and results were null (46, 50). In a non-athlete population, Ferrauti's data indicated that there were no differences in lactate threshold between concurrent and aerobic training groups following traditional resistance and novice marathon training (17). The effect of concurrent circuit training on lactate threshold remains unknown. While both aerobic training and circuit style resistance training enhance the variable, it is unknown whether these effects are additive.

Concurrent resistance training improves running economy in endurance-trained populations. In a group of females running 20-30 miles per week (a training volume similar to that performed in the present study), Johnston et al. found that adding a twelve week traditional (6-20 RM) resistance training program improved running economy by 4% when compared to run training alone (29). Numerous studies have examined the effect of concurrent plyometric style training on running economy in endurance trained populations. On two occasions, the addition of plyometrics to the routine of male distance runners enhanced running economy (50, 59). Once again, Ferrauti did not observe any differences in running economy between concurrent and aerobic training groups in response to concurrent traditional resistance training (17). The effect of adding circuit training to an aerobic training program on running economy in a recreationally active population is completely unknown.

Only one study has examined the effects of concurrent training on the major physiological determinants of endurance performance ($\text{VO}_{2\text{max}}$, lactate threshold, and running economy) in recreational marathon runners, and there were no additional increases observed with the addition of traditional resistance training (17). Concurrent resistance training programs are

not likely to alter $\text{VO}_{2\text{max}}$ or lactate threshold (8, 17, 20, 24, 26, 29, 41, 42, 43, 46, 50, 59), while they do have the potential to improve running economy in *endurance-trained* individuals (29, 50, 59). Concurrent circuit training is unlikely to increase $\text{VO}_{2\text{max}}$ compared to aerobic training alone (8, 24, 26, 29, 42, 43, 46, 50, 59), while the effect of concurrent circuit training on both lactate threshold and running economy is unknown. Performed on its own, circuit training has the potential to improve lactate threshold without the presence of aerobic training (16, 40). It remains to be seen whether the cardiovascular and metabolic adaptations of circuit and endurance training are additive.

Table 2.3 - Cardiovascular and Metabolic Adaptations to Concurrent Training

Author	Subjects	Workload	Duration	Style	AE	VO _{2max}	LT	RE
Gettman 1982 (19)	36 females 41 males CONC vs. S	3 sets of 12-15 reps 15 sec rest total body	12 wk 3 d/wk	Circuit	Running	↔	NA	NA
McCarthy 1995 (40)	30 sedentary males S (n=10) AE (n=10) CONC (n=10)	4 sets of 5-7 RM total body	10 wks 3 d/wk	Conventional	Cycling	↔	NA	NA
Johnston 1997 (28)	12 female distance runners CONC (n=6) vs. AE (n=6)	2-3 sets of 6-20 RM 2 min rest total body	12 wks 3 d/wk	Conventional	Running	↔	NA	↑4%
Bishop 1999 (8)	21 trained female cyclists(18-42 yrs) CONC (n=14) vs. AE(n=7)	5 sets of 2-8 reps @ 70-80% 1RM parallel squat only	12 wks 2 d/wk	Conventional	Cycling	↔	↔	NA
Paavolanien 1999 (44)	22 male distance runners CONC (n=12) vs. S (n=10)	30-200 contractions 15-90 min, 5-20 reps per set. Low-load lower-body plyometric training	9 wks 32% of running volume replaced	Plyometric	Running	↔	↔	↑8.1%
Hoff 2002 (25)	19 male cross-country Skiers CONC (n=9) vs. AE (n=10)	3 sets of 3-6 reps @85% 1RM modified cable pull-down only	8 wks 3 d/wk	Conventional	Cross- country skiing	↔	NA	↑
Millet 2002 (42)	15 triathletes CONC (n=7) vs. AE (n=8)	3-5 sets 3-5 RM lower body only	14 wks 2 d/wk	Conventional	Running Swimming Cycling	↔	NA	↑
Turner 2003 (58)	18 distance runners CONC (n=10) vs. AE (n=8)	10-20 reps 6 low-load plyometric exercises	6 wks 3 d/wk	Plyometric	Running	↔	NA	↑ 8%
Hamilton 2006 (23)	20 distance runners	3 sets explosive single leg jumps and alternating resisted sprints	5-7 wks 1-2 d/wk	Plyometric	Running	↔	NA	NA

CONC= Concurrent Training AE= Endurance Training S= Resistance Training

Table 2.3 – Cardiovascular and Metabolic Adaptations to Concurrent Training

Author	Subjects	Workload	Duration	Style	AE	VO_{2max}	LT	RE
Saunders 2006 (49)	15 male distance runners CONC (n=7) vs. AE (n=8)	30 min low-load lower-body plyometric training	9 wks 3 days/wk	Plyometric	Running	↔	↔	↑4.1%
Mikkola 2007 (41)	25 young distance runners CONC (n=13) AE (n=12)	2-3 sets 6-10 reps low-load plyometric	8 wks 19% of endurance volume	Conventional	Running	↔	NA	↔
Ferrauti 2010 (16)	22 recreational marathon runners CONC (n=11) vs. AE (n=11)	Leg/trunk exercises 4 sets 3-5 RM	8 wks 2 d/wk	Conventional	Running	↔	↔	↔

CONC= Concurrent Training AE= Endurance Training S= Resistance Training

Skeletal Muscle Architectural Adaptations to Exercise Training

Human skeletal muscle architecture is defined by several interrelated parameters including pennation angle (the angle at which muscle fibers are oriented between each tendon), muscle thickness (size: the distance between the superficial and deep borders of a muscle), and fascicle length (the length of bundled muscle fibers in series between each tendon) (39). Strength training alters all parameters of muscle architecture in a fashion that is likely to improve whole muscle function (3, 5, 9, 33, 52). Significant changes in muscle thickness, pennation angle, and fascicle length have been noted as early as 3 weeks into a progressive resistance exercise program (9, 52). Increases in muscle mass have been shown over a variety of resistance training programs (3, 5, 9, 33, 52). Thus not surprisingly, Abe et al. reported marked increases in muscle thickness following 12 weeks of traditional resistance training (3). Subsequent studies reported consistent findings accompanied by a 16%-25% increase in fascicle length in response to a similar resistance-training program. The authors also noted that while not significant, there was a slight decrease in pennation angle (5, 9).

There is no existing data on the effects of run training on skeletal muscle architecture. However, there are architectural differences between the leg muscles of sprinters and distance runners. Specifically the vastus lateralis and lateral gastrocnemius of sprinters are thicker, more finely pennated (smaller angle relative to the aponeuroses), and have longer fascicles when compared to endurance runners (4). These data infer that a relationship exists between running specificity and architectural adaptation. Furthermore, when stratified according to ability, the best sprinters displayed the most extreme architectural characteristics; implying that fascicle lengthening facilitates

improved muscle shortening velocity and running performance. However, this data by its nature does not address whether these architectural differences are a product of genetic predisposition or an adaptation to training. While aerobic training decreases single fiber and whole muscle size (38, 58), there is limited data on prolonged aerobic training's effect on pennation angle and fascicle length. Indeed, our laboratory recently observed architectural changes in the lateral gastrocnemius (calf) with marathon run training (Murach and Luden, unpublished observations). Skeletal muscle thickness was greater following the training intervention in both the vastus lateralis ($3.8 \pm 6.7\%$) and later gastrocnemius ($6.6 \pm 11.1\%$). Lateral gastrocnemius pennation angle also increased ($19.31 \pm 2.2\%$) with marathon training while vastus lateralis remained unchanged. Lateral gastrocnemius fascicle length decreased ($14.5 \pm 44.6\%$) from pre to post with no change in the vastus lateralis. These data are the first to provide evidence that the architectural characteristics of endurance athletes are not solely the result of genetic predisposition and likely involve a training adaptation component.

It remains unknown whether architectural adaptations to training are linked to bioenergetic adaptations. However, Blazeovich proposes that pennate muscle rotates during contraction, and an increase in pennation angle potentially orients fibers at an optimal contractile length (9). This could have implications both on the oxygen demand at a given work rate (running economy) and the metabolic turnover associated with the intensity (lactate production), thereby decreasing fatigueability. Whether these adaptations are influenced by concurrent aerobic and resistance exercise is unknown.

Table 2.4 – Skeletal Muscle Architectural Adaptations to Exercise Training

Author	Subjects	Exercise	Thickness	Pennation Angle	Fasc. Length
Kawakami 1995 (31)	5 males	Resistance 16 wks elbow extension only	↑	↑	↔
Starkey 1996 (55)	48 untrained adults S (n=38) vs. CON (n=10)	Resistance 14 wks 1-3 sets 8-12 reps to fatigue	↑	NA	NA
Abe 2000 (3)	40 untrained adults S (n= 27) vs. CON (n=13)	Resistance 12 wks 3 d/wk 3 sets 8-12 reps 60-70% 1RM	↑ 10-31% upper ↑ 7-9% lower	NA	NA
Abe 2000 (4)	47 elite male track athletes Sprinters (n=23) vs Distance runners (n=24)	NA	Distance ↓ than sprint	Distance ↑ than sprint	Distance ↓ than sprint
Blazevich 2003 (9)	23 competitive athletes	Resistance 5 wks 2 days/wk 6-10 reps of 45-90% 1RM	↑	↔	↑ 24.9%
Alegre 2006 (5)	36 male physical education students S (n=16) vs. CON (n=14)	Resistance 13 wks 3 days/wk 3-4 sets of 6-12 reps	↑ 6.9%	↔	↑ 10.5%
Seynnes 2007 (51)	7 recreationally active individuals	Resistance 7 wks 3 days/wk 4 sets 7 reps bilateral leg extension only	NA	↑ 9.9%	↑ 7.7%

S= Resistance Training CON= Control

Summary

Cardiovascular and metabolic adaptations to aerobic training are vast and well documented (7, 11, 12, 15, 18, 37, 38, 40, 49, 53, 55, 58, 61). $\text{VO}_{2\text{max}}$ and lactate threshold, for example can be improved by running as little as 6 miles per week in previously sedentary individuals (48). Both $\text{VO}_{2\text{max}}$ and running economy can improve in response to beginning marathon training, while less is known about the effects on lactate threshold (38, 58).

$\text{VO}_{2\text{max}}$ is unlikely to improve through traditional resistance training alone (10, 21, 25, 35, 37, 40). However, circuit training improves $\text{VO}_{2\text{max}}$ (23, 24, 62). Likewise, traditional resistance training programs alone are unlikely to impact lactate threshold (11) while circuit training programs can improve lactate threshold (16, 40). Although running economy is a common variable in the context of aerobic exercise training, nothing is known about the effects of any form of resistance training alone on running economy.

Concurrent traditional resistance training programs are not likely to improve $\text{VO}_{2\text{max}}$ or lactate threshold in *endurance-trained* populations (8, 17, 20, 24, 26, 29, 41, 42, 43, 46, 50, 59). Similarly, concurrent circuit training is unlikely to increase $\text{VO}_{2\text{max}}$ compared to aerobic training alone (8, 24, 26, 29, 42, 43, 46, 50, 59). However, the effect of concurrent resistance training on lactate threshold in *untrained populations* remains unknown. Resistance training improves running economy in *endurance trained* individuals (29, 50, 59), while the effect of concurrent traditional or circuit training on running economy in *untrained populations* has not been studied. Only one study has examined the effects of concurrent training on the major physiological determinants of endurance performance ($\text{VO}_{2\text{max}}$, lactate threshold, and running economy) in recreational

marathon runners, and there were no additional increases observed with the addition of traditional resistance training (17). Circuit training may have the potential to improve lactate threshold without the presence of aerobic training (16, 40). The effect of concurrent circuit training on both lactate threshold and running economy in recreational marathon runners is unknown.

The impact of skeletal muscle structure on distance running is a novel area. Strength training alters all parameters of muscle architecture in a fashion that is likely to improve whole muscle function (3, 5, 28, 46). Sprinters have thicker musculature, smaller pennation angles and longer fascicles than endurance runners (4). Indeed, our laboratory recently observed marked architectural changes in the lateral gastrocnemius (calf) with marathon run training (Murach and Luden, unpublished observations). However, whether these adaptations are influenced by concurrent resistance training, or if they are linked to cardiovascular and metabolic adaptations to training is unknown.

The current project is the first to examine cardiovascular and metabolic adaptations to concurrent endurance and circuit training. This will be the first study to investigate skeletal muscle architectural adaptations to concurrent training. In addition, the data will add to the limited body of literature regarding skeletal muscle architectural adaptations to aerobic training, and potentially provide further insight into a link between cardiovascular, metabolic and skeletal muscle architectural adaptations to training.

CHAPTER THREE

METHODOLOGY

Subjects

Thirteen subjects (6 males, 7 females) recruited from James Madison University, completed each phase of the training program and the marathon. Nine subjects completed the 15 weeks of progressive marathon-training (AE), whereas 4 subjects participated in the 9-wk circuit training program (CONC), in addition to the run training (Figure 1). The subjects were 21 ± 1 yr, 171 ± 2 cm, 65 ± 2 kg, with a $\text{VO}_{2\text{max}}$ of 55 ± 2 ml/kg/min. An informed consent approved by the James Madison University Institutional Review Board was completed before any testing or training.

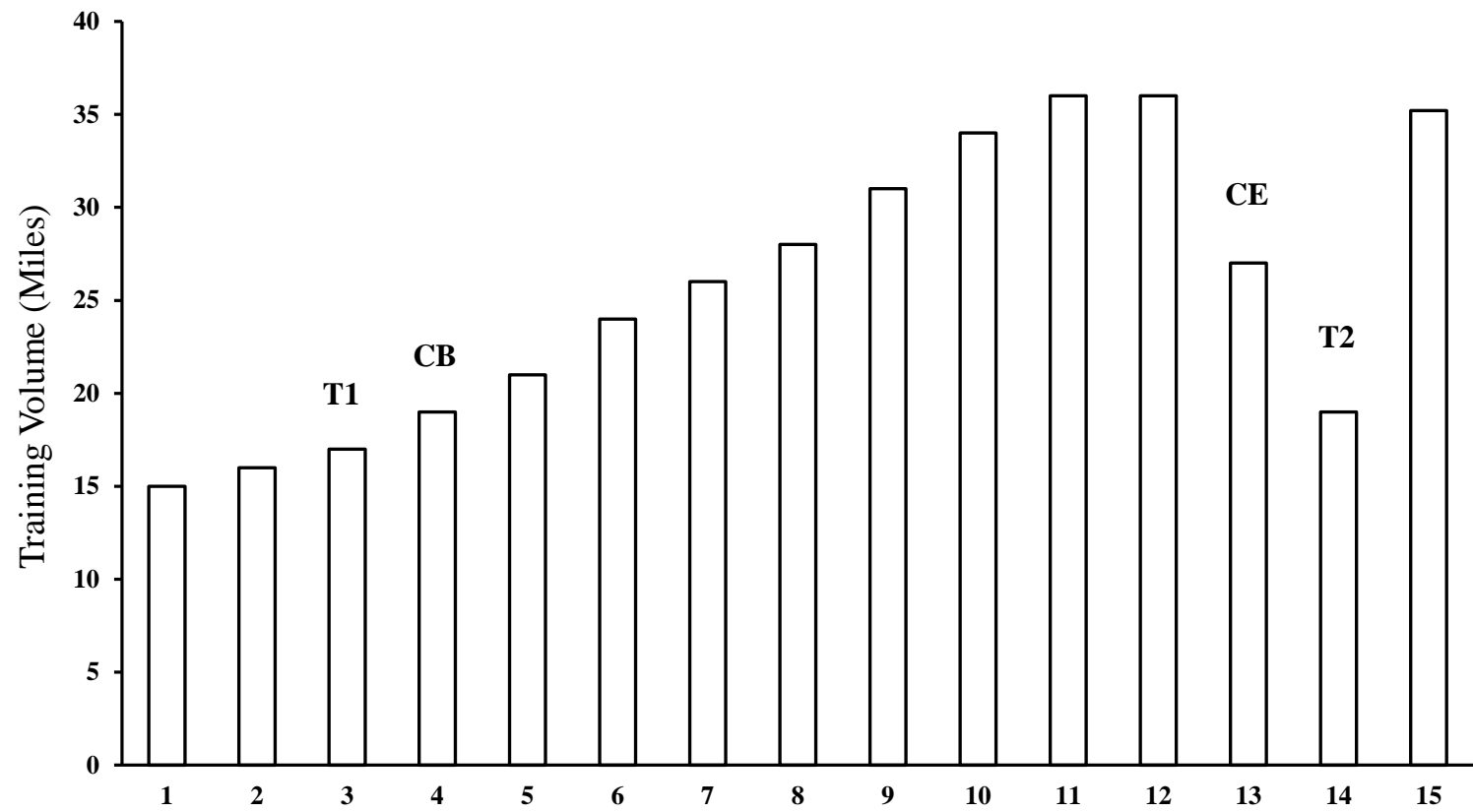
Experimental Design/Training Program

Cardiovascular, metabolic and skeletal muscle architectural parameters were assessed at two different time points during a 15-wk marathon-training program (Figure 3.1). Testing was implemented at week 3 and week 14 of the marathon-training program. The logistics of the marathon-training program are identical to those used by the Ball State Human Performance Laboratory (57), which was modeled after the original training program implemented at the University of Northern Iowa. The subjects ($n=13$) were a subset of students from a university course designed to physically and mentally prepare each student to complete their first marathon. The 4 days/wk training regimen was characterized by two-phases. The first phase consisted of a 13-wk training period that progressively increased the overall training volume by $\sim 140\%$ relative to week 1, with

the peak weekly running volume of 36 miles (58.3 km) occurring on weeks 12 and 13. The second training phase included 3 weeks of reduced training volume (taper) leading up to the marathon event. Compared with week 13, running volume was progressively decreased until total weekly volume was reduced by 80% relative to week 13, the week before the marathon.

In addition to the run training the CONC group (n=4) completed a 9-wk circuit resistance training program (3 days a week) characterized by high repetitions (15-20), and short rest periods (work: rest = 40 sec: 20 sec). The subgroup consisted of self-selected volunteers. The routine consisted of 4 lower body (leg press, leg extension, leg curl, and calve raise), four upper body (chest press, shoulder press, seated row, and lat pull-down) and two core exercises (weighted abdominal crunch and back extension). The resistance was increased by 2 to 23 kg (5 to 50 lbs) on any given exercise, upon completion complete 20 repetitions on any 2 consecutive sets for that exercise. Conversely, subjects were instructed to decrease the resistance by 2 to 23 kg (5 to 50 lbs), on any given exercise, if unable to complete 15 repetitions on any one set. The subjects were required to complete two supervised sessions and one unsupervised session a week for the duration of the 9-week period. The unsupervised session was designed to replicate the same exercises implemented during the supervised sessions, similar rest to work ratios, and same set/rep breakdown. All sets and repetitions for each exercise from both supervised and unsupervised sessions were recorded in weekly logs. To assess changes in muscular strength with circuit training, subjects performed a 1-repetition maximum test for the chest press, leg press and leg extension during the initial and final supervised session of the program. Subjects performed 10-15 repetitions at 50% of their perceived

one-rep max, rested for 2 minutes, and then attempted one-repetition at 100% of their perceived 1-rep max. Resistance increased by 2 to 23 kg (5-50 lbs) until the subject could not successfully complete one full repetition.

FIGURE 3.1 – General Study Design

T1= Pre Testing T2= Post Testing CB= Circuit Training Begins CE= Circuit Training Ends

Testing Procedures

Cardiorespiratory Fitness (VO_{2max} , Lactate Threshold, Submaximal Blood Lactate and Running Economy)

Subjects performed a graded exercise test to determine maximal oxygen uptake (VO_{2max}), submaximal blood lactate concentrations, lactate threshold and running economy on a Stairmaster Quinton treadmill (Vancouver, WA) at week 3 and week 14 of the marathon-training program. Oxygen consumption (VO_2), respiratory exchange ratio (RER) and ventilation (VE) were continuously monitored with a Sensormedics Spectra (Yorba Linda, CA) metabolic cart. Heart rate was monitored using a Suunto (Finland) heart rate monitor. The treadmill protocol consisted of two discontinuous phases.

The treadmill protocol consisted of two discontinuous phases. The first phase was used to assess submaximal blood lactate concentrations and lactate threshold. Specifically, subjects performed a 5-minute walking warm up at 5.6 kph (3.5 mph). Following the warm-up, the treadmill was set at an individualized velocity that corresponded to the speed that was ‘typically performed during a 60-minute training run’. The speed was incrementally increased by 24-32 sec/km (15-20 sec/mile) in 3-minute stages. Subjective ratings of exertion (RPE) were obtained using the Borg RPE scale (numerically rated from 6-20) in the final minute of each stage. At the end of each 3-minute stage, subjects were instructed to straddle the treadmill for a 1-minute rest period. During this rest period capillary blood lactate levels taken via finger stick were assessed using an YSI 2300 STAT glucose/lactate analyzer to determine submaximal blood lactate concentrations and lactate threshold (> 3.5 mmol). Multiple lactate cutoffs were assessed, and ultimately 3.5 mmol was selected because it was the only criteria achieved by all

subjects. Once blood lactate levels exceed 3.5 mmol/L the treadmill was stopped and subjects rested for a period of 15 minutes. The speed preceding the point at which lactate levels exceed 3.5 mmol was deemed $LT_{3.5\text{mmol}}$. Running economy was determined by assessing VO_2 at a fixed submaximal intensity (mean speed = $12.3 \pm 0.3\text{kph}$). Fractional utilization was determined by calculating the percentage of $\text{VO}_{2\text{max}}$ being used at that same intensity.

The second phase was used to assess $\text{VO}_{2\text{max}}$. Following 15 minutes of passive recovery subjects completed a 3-minute walking warm-up at 5.6 kph (3.5 mph). Immediately following the walking-warm up, the treadmill was set at a speed corresponding with the penultimate stage of phase one. Each subsequent 2-minute stage was accompanied by a 2% increase in grade until volitional exhaustion.

Maximal Voluntary Contraction (MVC)

Subjects performed a MVC test at week 3 and week 14 of the marathon-training program. Following a 5-minute self-paced walking warm-up, subjects were positioned in a custom-built leg extension machine, equipped with a force transducer and controlled via computer with custom software. Subjects were secured with a lap belt and their flexed right ankle was fixed to a padded bar with a velcro strap. Subjects were prompted to exert maximum 1-legged force against the bar for three seconds on 3 separate occasions with each repetition separated by 1 minute of rest. A fourth repetition was performed if the top 2 force values varied by more than 20 Newtons. Peak force was recorded in Newtons and the highest value was utilized for analysis.

Skeletal Muscle Ultrasound

Skeletal muscle thickness, pennation angle, and fascicle length were measured *in vivo* at rest in all subjects at week 3 and week 14 of the marathon-training program. Ultrasonography of the right vastus lateralis (VL) and lateral gastrocnemius (LG) was performed using a Shenzhen Mindray DC-6 (Nanshan, Shenzhen, China) machine in B-mode with a 10 MHz capacity linear array transducer. To avoid potential variability in muscle architecture resulting from hemodynamics, subjects rested in a seated position for 10 minutes prior to the vastus lateralis measurement and for 5 minutes in the prone position for the subsequent gastrocnemius measurement.

Vastus Lateralis

During the initial visit, the mid-muscle belly of the VL was identified and recorded for subsequent visits using methodology adapted from Kawakami et al (24). The distance between the bony protuberance of the greater trochanter of the femur to the prominence of the lateral femoral condyle was determined. Midway between these anatomical landmarks, a vertical line was drawn from the lateral border of the patella past the midway point of the greater trochanter and femoral condyle. A perpendicular line was then drawn to that midway point, creating an intersection on the middle aspect of the VL. The midway point along the perpendicular line was identified and marked with permanent marker. This point is approximately mid-muscle belly of the VL where images were captured.

The ultrasound head was angled until the aponeuroses of the VL could be clearly delineated. The transducer was then quickly and firmly placed against the skin to elicit

indentation. With the skin indentation momentarily visible, the gel was wiped away and the outline of the indentation was marked with permanent marker, denoting the location for future imaging. Following identification of the VL site, subjects sat upright on a table with a hip angle of 90 degrees and the ankle affixed at 90 degrees. On the 7.5 MHz probe frequency setting and using a liberal amount of ultrasound gel, the investigator placed the head of the ultrasound over the skin while avoiding dermal contact and pressure to mitigate muscle thickness alterations.

Lateral Gastrocnemius

During the initial visit, mid-muscle belly of the lateral gastrocnemius was identified and recorded for subsequent visits. The distance between the bony protuberance of the anklebone and the prominence of the lateral femoral condyle (along the skin fold behind the knee) was measured. The first longitudinal reference was placed along this axis in a position 30% distal to the lateral femoral condyle. One quarter the distance between the medial and lateral condyle of the femur on the posterior and lateral aspect of the knee (along the skin fold) provided the second horizontal reference point for measurement. A line was drawn horizontally and medially from the first reference point and vertically and distally from the second reference point to create an intersection approximately mid-belly of the lateral gastrocnemius where images were taken.

With the subject prone and ankle affixed at 90 degrees against a wall, the ultrasound head was angled until the aponeuroses of the gastrocnemius could be clearly delineated. The same protocol described above (VL) was applied to identify the gastrocnemius insonation site.

Image Analysis

Ultrasound image analysis was performed using ImageJ64 software (National Institute of Health, USA) on a Macintosh computer. Muscle thickness was determined by measuring the distance between the superficial and deep aponeuroses of the muscle at three points along the length of the muscle belly, perpendicular to the aponeurosis. The pennation angle of the fascicles was also measured at three different locations within the muscle belly (superficial, middle, and deep) and averaged. Fascicle length was estimated using a prediction equation outlined by Abe et al (4). The technician was blinded for subject number, group, date time and muscle prior to analysis.

Statistical Analyses

A series of 2x2 repeated measures ANOVAs were performed to examine the interactive effects of training intervention (AE vs. CONC) and time (pre-to-post training) on $\text{VO}_{2\text{max}}$, submaximal blood lactate concentration, lactate threshold, running economy, MVC, muscle thickness, pennation angle, and fascicle length. Data was tested for normality using a Shapiro-Wilk's test. For data that was not normally distributed, a related-samples Wilcoxon Signed Ranks Test was applied. Percent change scores were calculated to compare the magnitude of change in each variable between groups. Pearson correlation coefficients were calculated to determine relationships between changes in architectural and cardiovascular/metabolic parameters. Significance was set at $p < 0.05$.

CHAPTER FOUR
MANUSCRIPT

Aerobic and Skeletal Muscle Architectural Adaptations to
Concurrent Marathon and Circuit Resistance Training

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Running Head: Concurrent Training, Marathon Training, Determinants of Endurance
Performance and Skeletal Muscle Architecture

ABSTRACT

Purpose: The purpose of this investigation was to examine performance-related physiological adaptations ($\text{VO}_{2\text{max}}$, Lactate Threshold, and Running Economy) and skeletal muscle architectural changes (muscle thickness, pennation angle, and fascicle length) of the vastus lateralis (VL) and lateral gastrocnemius (LG) to marathon training with and without a concurrent circuit resistance-training program. **Methods:** Thirteen subjects (21 ± 1 yrs, 171 ± 2 cm, 65 ± 2 kg, 55 ± 2 ml/kg/min) completed a 15-week progressive marathon-training program. Nine subjects completed the 15 weeks of progressive marathon-training alone (AE), while 4 subjects participated in the 9-week circuit training program (CONC), in addition to the run training. $\text{VO}_{2\text{max}}$, lactate threshold, running economy, muscle thickness, pennation angle and fascicle length were assessed before and after training. 2x2 repeated measures ANOVAs and Wilcoxon Signed-Rank Tests were used to test the effects of the concurrent training intervention (AE vs. CONC) and general training program (pre vs. post training). Pearson correlations were utilized to examine relationships between changes in architectural and cardiovascular/metabolic parameters. **Results:** Absolute $\text{VO}_{2\text{max}}$ (L/min) increased in ALL with training (3.58 ± 0.18 vs. 3.73 ± 0.22 ; $p=0.018$), with a 9% increase in CONC (3.52 ± 0.38 L/min vs. 3.87 ± 0.50 L/min; $p=0.031$) and no change in AE. Lactate threshold increased significantly in ALL post-training (12.4 ± 0.3 kph vs. 13.2 ± 0.3 kph; $p=0.012$), with no differences between groups. There were no changes in running economy [submax VO_2 (ml/kg/min)]. LG pennation angle increased in ALL ($17 \pm 1.0^\circ$; $p=0.056$) with no differences between groups, while VL pennation angle did not change. There were no changes in muscle thickness or fascicle length in the VL or LG.

Conclusion: Notwithstanding the small sample size, concurrent marathon and circuit training appears to increase absolute $\text{VO}_{2\text{max}}$ to a greater extent than marathon training alone. Marathon training increases LG pennation angle, and the change is not influenced by concurrent circuit resistance training. These findings suggest that that it can be beneficial for beginning marathon runners to supplement with concurrent circuit training programs, and that LG pennation angle is highly sensitive to endurance run training.

INTRODUCTION

Marathon running has grown in popularity over the past few decades, with nearly half a million individuals completing the marathon distance (42.2 km) in the U.S. in 2009 (35). Three primary physiological determinants of marathon performance include $\text{VO}_{2\text{max}}$, lactate threshold, and movement economy. While not definitive predictors of performance, elite endurance athletes possess high aerobic capacities, fast sustainable running paces before the rate of lactate production exceeds the rate of lactate removal, and low oxygen requirements at given running velocities. Importantly, improvements in $\text{VO}_{2\text{max}}$, lactate threshold and running economy have all been demonstrated in response to aerobic training (7, 10, 11, 14, 17, 35, 36, 38, 47, 51, 53, 56, 59). Both $\text{VO}_{2\text{max}}$ and running economy have the potential to improve in response to *beginning* marathon training, while less is known about the effects on lactate threshold (36, 56).

In addition to run-training, many marathon programs incorporate some form of resistance-training. The physiological benefits of resistance training are also well documented and include increases in skeletal muscle strength and resting metabolic rate (2, 3, 5, 18, 31, 54). $\text{VO}_{2\text{max}}$ is largely unaffected by traditional resistance training (progressive 8-12 repetition sets with ample rest periods) alone (11, 22, 25, 35, 36, 39). Traditional resistance training programs performed on their own are unlikely to impact lactate threshold (11).

Circuit training (15-20+ repetition sets with limited rest periods) has the potential to increase $\text{VO}_{2\text{max}}$ (19, 20, 22, 23, 60) and lactate threshold (16, 39). Little is known about the effects of any form of resistance training alone on running economy. Only one study has examined the effects of concurrent resistance training on the major

physiological determinants of endurance performance ($\text{VO}_{2\text{max}}$, lactate threshold, and running economy) in recreational marathon runners, and produced no physiological improvements over run-training alone (17). The potential for circuit-training to augment the physiological factors that are essential for marathon success is unknown.

Unlike the primary determinants of running performance, the impact of aerobic training on skeletal muscle architecture is not well understood. Human skeletal muscle function and consequently whole body function is potentially influenced by muscle architecture (43). Human skeletal muscle architecture is defined by several interrelated parameters including muscle thickness (size: the distance between the superficial and deep borders of a muscle), pennation angle (the angle at which muscle fibers are oriented between each tendon), and fascicle length (the length of bundled muscle fibers in series between each tendon) (43). Resistance training alters all these architectural parameters (3, 7, 9, 32, 51, 55). Significant changes in muscle thickness, pennation angle, and fascicle length have been noted as early as 3 weeks into a progressive resistance exercise program (51). Further, sprinters have thicker musculature, smaller pennation angles and longer fascicles than endurance runners (4). Indeed, our laboratory recently observed marked architectural changes in the lateral gastrocnemius (calf) with marathon run training (Murach and Luden, unpublished observations). Architectural adaptations may support the ability to continuously run 42.2 km (26.2 miles). However, whether these adaptations are influenced by any form of concurrent resistance exercise is unknown.

The primary objectives of the current study were to test the hypotheses that when compared to running alone, concurrent circuit-training would: 1) improve $\text{VO}_{2\text{max}}$, 2) improve lactate threshold, 3) improve running economy and 4) influence skeletal muscle

architecture.

METHODS

Subjects

Thirteen subjects (6 males, 7 females) recruited from James Madison University, completed each phase of the training program, while 12 of 13 subjects completed the marathon. Nine subjects completed the 15 weeks of progressive marathon-training (AE), whereas 4 subjects participated in the 9-wk circuit training program (CONC), in addition to the run training (Figure 1). The subjects were 21 ± 1 yr, 171 ± 2 cm, 65 ± 2 kg, with a $\text{VO}_{2\text{max}}$ of 55 ± 2 ml/kg/min. An informed consent approved by the James Madison University Institutional Review Board was completed before any testing or training.

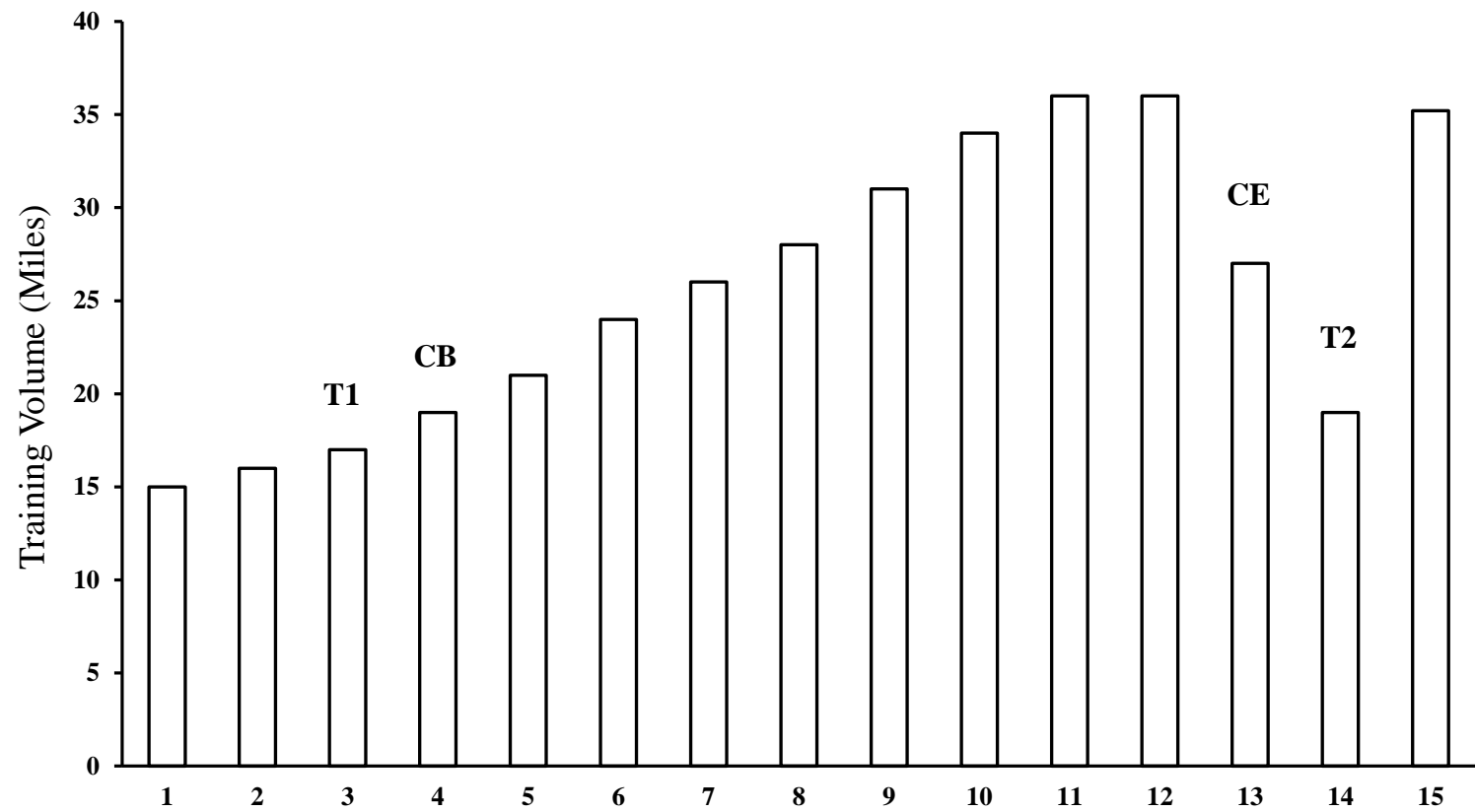
Experimental Design/Training Program

Cardiovascular, metabolic and skeletal muscle architectural parameters were assessed at two different time points during a 15-wk marathon-training program (Figure 3.1). Testing was implemented at week 3 and week 14 of the marathon-training program. The logistics of the marathon-training program are identical to those used by the Ball State Human Performance Laboratory (57), which was modeled after the original training program implemented at the University of Northern Iowa. The subjects ($n=13$) were a subset of students from a university course designed to physically and mentally prepare each student to complete their first marathon. The 4 days/wk training regimen was characterized by two-phases. The first phase consisted of a 13-wk training period that progressively increased the overall training volume by $\sim 140\%$ relative to week 1, with the peak weekly running volume of 36 miles (58.3 km) occurring on weeks 12 and 13. The second training phase included 3 weeks of reduced training volume (taper) leading

up to the marathon event. Compared with week 13, running volume was progressively decreased until total weekly volume was reduced by 80% relative to week 13, the week before the marathon.

In addition to the run training the CONC group (n=4) completed a 9-wk circuit resistance training program (3 days a week) characterized by high repetitions (15-20), and short rest periods (work: rest = 40 sec: 20 sec). The subgroup consisted of self-selected volunteers. The routine consisted of 4 lower body (leg press, leg extension, leg curl, and calve raise), four upper body (chest press, shoulder press, seated row, and lat pull-down) and two core exercises (weighted abdominal crunch and back extension). The resistance was increased by 2 to 23 kg (5 to 50 lbs) on any given exercise, upon completion complete 20 repetitions on any 2 consecutive sets for that exercise. Conversely, subjects were instructed to decrease the resistance by 2 to 23 kg (5 to 50 lbs), on any given exercise, if unable to complete 15 repetitions on any one set. The subjects were required to complete two supervised sessions and one unsupervised session a week for the duration of the 9-week period. The unsupervised session was designed to replicate the same exercises implemented during the supervised sessions, similar rest to work ratios, and same set/rep breakdown. All sets and repetitions for each exercise from both supervised and unsupervised sessions were recorded in weekly logs. To assess changes in muscular strength with circuit training, subjects performed a 1-repetition maximum test for the chest press, leg press and leg extension during the initial and final supervised session of the program. Subjects performed 10-15 repetitions at 50% of their perceived one-rep max, rested for 2 minutes, and then attempted one-repetition at 100% of their perceived 1-rep max. Resistance increased by 2 to 23 kg (5-50 lbs) until the subject could

not successfully complete one full repetition.

FIGURE 4.1 – General Study Design

T1= Pre Testing T2= Post Testing CB= Circuit Training Begins CE= Circuit Training Ends

Testing Procedures

Cardiorespiratory Fitness (VO_{2max} , Lactate Threshold, Submaximal Blood Lactate and Running Economy)

Subjects performed a graded exercise test to determine maximal oxygen uptake (VO_{2max}), submaximal blood lactate concentrations, lactate threshold and running economy on a Stairmaster Quinton treadmill (Vancouver, WA) at week 3 and week 14 of the marathon-training program. Oxygen consumption (VO_2), respiratory exchange ratio (RER) and ventilation (VE) were continuously monitored with a Sensormedics Spectra (Yorba Linda, CA) metabolic cart. Heart rate was monitored using a Suunto (Finland) heart rate monitor. The treadmill protocol consisted of two discontinuous phases.

The treadmill protocol consisted of two discontinuous phases. The first phase was used to assess submaximal blood lactate concentrations and lactate threshold. Specifically, subjects performed a 5-minute walking warm up at 5.6 kph (3.5 mph). Following the warm-up, the treadmill was set at an individualized velocity that corresponded to the speed that was ‘typically performed during a 60-minute training run’. The speed was incrementally increased by 24-32 sec/km (15-20 sec/mile) in 3-minute stages. Subjective ratings of exertion (RPE) were obtained using the Borg RPE scale (numerically rated from 6-20) in the final minute of each stage. At the end of each 3-minute stage, subjects were instructed to straddle the treadmill for a 1-minute rest period. During this rest period capillary blood lactate levels taken via finger stick were assessed using an YSI 2300 STAT glucose/lactate analyzer to determine submaximal blood lactate concentrations and lactate threshold (> 3.5 mmol). Multiple lactate cutoffs were assessed, and ultimately 3.5 mmol was selected because it was the only criteria achieved by all

subjects. Once blood lactate levels exceed 3.5 mmol/L the treadmill was stopped and subjects rested for a period of 15 minutes. The speed preceding the point at which lactate levels exceed 3.5 mmol was deemed $LT_{3.5\text{mmol}}$. Running economy was determined by assessing VO_2 at a fixed submaximal intensity (mean speed = $12.3 \pm 0.3\text{kph}$). Fractional utilization was determined by calculating the percentage of $VO_{2\text{max}}$ being used at that same intensity.

The second phase was used to assess $VO_{2\text{max}}$. Following 15 minutes of passive recovery subjects completed a 3-minute walking warm-up at 5.6 kph (3.5 mph). Immediately following the walking-warm up, the treadmill was set at a speed corresponding with the penultimate stage of phase one. Each subsequent 2-minute stage was accompanied by a 2% increase in grade until volitional exhaustion.

Maximal Voluntary Contraction (MVC)

Subjects performed a MVC test at week 3 and week 14 of the marathon-training program. Following a 5-minute self-paced walking warm-up, subjects were positioned in a custom-built leg extension machine, equipped with a force transducer and controlled via computer with custom software. Subjects were secured with a lap belt and their flexed right ankle was fixed to a padded bar with a velcro strap. Subjects were prompted to exert maximum 1-legged force against the bar for three seconds on 3 separate occasions with each repetition separated by 1 minute of rest. A fourth repetition was performed if the top 2 force values varied by more than 20 Newtons. Peak force was recorded in Newtons and the highest value was utilized for analysis.

Skeletal Muscle Ultrasound

Skeletal muscle thickness, pennation angle, and fascicle length were measured *in vivo* at rest in all subjects at week 3 and week 14 of the marathon-training program. Ultrasonography of the right vastus lateralis (VL) and lateral gastrocnemius (LG) was performed using a Shenzhen Mindray DC-6 (Nanshan, Shenzhen, China) machine in B-mode with a 10 MHz capacity linear array transducer. To avoid potential variability in muscle architecture resulting from hemodynamics, subjects rested in a seated position for 10 minutes prior to the vastus lateralis measurement and for 5 minutes in the prone position for the subsequent gastrocnemius measurement.

Vastus Lateralis

During the initial visit, the mid-muscle belly of the VL was identified and recorded for subsequent visits using methodology adapted from Kawakami et al (24). The distance between the bony protuberance of the greater trochanter of the femur to the prominence of the lateral femoral condyle was determined. Midway between these anatomical landmarks, a vertical line was drawn from the lateral border of the patella past the midway point of the greater trochanter and femoral condyle. A perpendicular line was then drawn to that midway point, creating an intersection on the middle aspect of the VL. The midway point along the perpendicular line was identified and marked with permanent marker. This point is approximately mid-muscle belly of the VL where images were captured.

The ultrasound head was angled until the aponeuroses of the VL could be clearly delineated. The transducer was then quickly and firmly placed against the skin to elicit

indentation. With the skin indentation momentarily visible, the gel was wiped away and the outline of the indentation was marked with permanent marker, denoting the location for future imaging. Following identification of the VL site, subjects sat upright on a table with a hip angle of 90 degrees and the ankle affixed at 90 degrees. On the 7.5 MHz probe frequency setting and using a liberal amount of ultrasound gel, the investigator placed the head of the ultrasound over the skin while avoiding dermal contact and pressure to mitigate muscle thickness alterations.

Lateral Gastrocnemius

During the initial visit, mid-muscle belly of the lateral gastrocnemius was identified and recorded for subsequent visits. The distance between the bony protuberance of the anklebone and the prominence of the lateral femoral condyle (along the skin fold behind the knee) was measured. The first longitudinal reference was placed along this axis in a position 30% distal to the lateral femoral condyle. One quarter the distance between the medial and lateral condyle of the femur on the posterior and lateral aspect of the knee (along the skin fold) provided the second horizontal reference point for measurement. A line was drawn horizontally and medially from the first reference point and vertically and distally from the second reference point to create an intersection approximately mid-belly of the lateral gastrocnemius where images were taken.

With the subject prone and ankle affixed at 90 degrees against a wall, the ultrasound head was angled until the aponeuroses of the gastrocnemius could be clearly delineated. The same protocol described above (VL) was applied to identify the gastrocnemius insonation site.

Image Analysis

Ultrasound image analysis was performed using ImageJ64 software (National Institute of Health, USA) on a Macintosh computer. Muscle thickness was determined by measuring the distance between the superficial and deep aponeuroses of the muscle at three points along the length of the muscle belly, perpendicular to the aponeurosis. The pennation angle of the fascicles was also measured at three different locations within the muscle belly (superficial, middle, and deep) and averaged. Fascicle length was estimated using a prediction equation outlined by Abe et al (4). The technician was blinded for subject number, group, date time and muscle prior to analysis.

Statistical Analyses

A series of 2x2 repeated measures ANOVAs were performed to examine the interactive effects of training intervention (AE vs. CONC) and time (pre-to-post training) on $\text{VO}_{2\text{max}}$, submaximal blood lactate concentration, lactate threshold, running economy, MVC, muscle thickness, pennation angle, and fascicle length. Data was tested for normality using a Shapiro-Wilk's test. For data that was not normally distributed, a related-samples Wilcoxon Signed Ranks Test was applied. Percent change scores were calculated to compare the magnitude of change in each variable between groups. Pearson correlation coefficients were calculated to determine relationships between changes in architectural and cardiovascular/metabolic parameters. Significance was set at $p < 0.05$.

RESULTS

Marathon Performance

Twelve out of 13 subjects completed the marathon with an average time of 4 hours and 19 minutes. Finishing times ranged between 3 hours and 33 minutes to 4 hours and 49 minutes.

VO_{2max} & Lactate Threshold

Absolute VO_{2max} (L/min) increased in ALL from pre to post-training ($p=0.018$), with 9% increase in CONC and no change in AE ($p=0.031$) (Figure 4.2). Conversely, relative VO_{2max} (ml/kg/min) was not influenced by training. LT_{3.5mmol} increased by 5% in ALL post-training ($p=0.012$), with no differences between groups. VE_{max} and HR max did not change as a result of training (Table 4.1).

Running Economy & Submaximal Lactate Concentrations

There were no changes in running economy or fractional O₂ utilization. Submaximal lactate concentrations were 22% lower with training in ALL ($p=0.003$), with no differences between groups. RER decreased in ALL with training ($p=0.019$) (Table 4.2).

Muscular Strength

There were no changes in MVC with training. CONC improved 1-repetition maximum on the Chest Press (67 ± 17 kg vs. 73 ± 19 kg, $p=0.032$), Leg Press (137 ± 29 kg vs. 159 ± 28 kg, $p=0.012$) and Leg Extension (77 ± 10 kg vs. 84 ± 10 kg, $p=0.031$).

Skeletal Muscle Architecture

Gastrocnemius pennation angle increased in ALL ($p=0.056$), with no differences between groups (Figure 4.3). There were no changes in muscle thickness or fascicle length in the Gastrocnemius. There were no changes in muscle thickness, pennation angle or fascicle length in the Vastus Lateralis (Table 4.3).

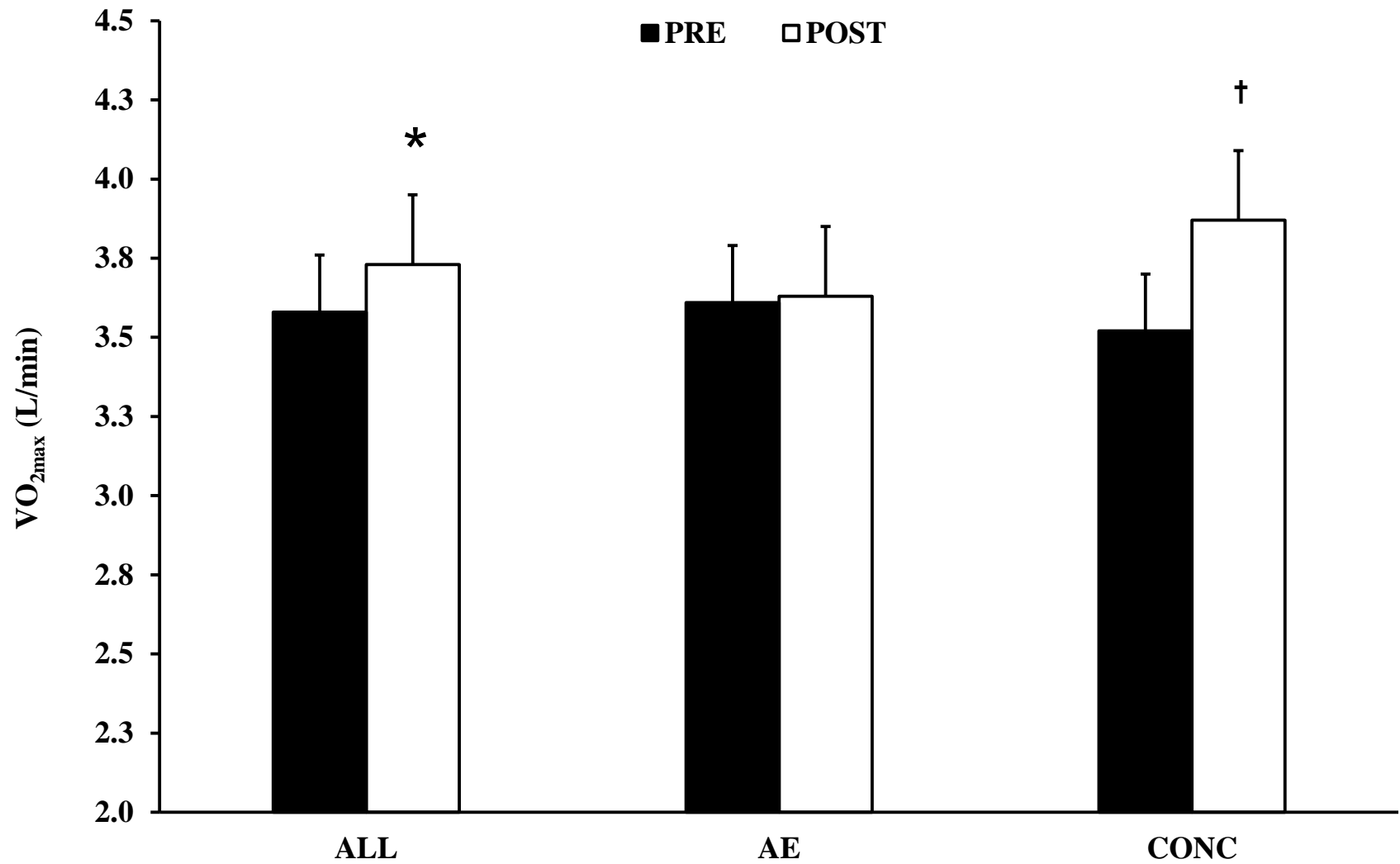
Relationship between changes in LG Pennation Angle & Changes in VO_{2max} , Lactate Threshold, Submaximal Lactate Concentrations, and Running Economy

There was an inverse relationship between the changes in LG pennation angle and the decrease in submaximal lactate concentrations in ALL ($r=-.621$, Figure 4.4). There were no observed relationships between the increase in LG pennation angle and VO_{2max} , lactate threshold or running economy.

TABLE 4.1. Maximal cardiovascular and metabolic responses to treadmill exercise before and after training

GROUP	ALL		AE		CONC	
	Pre	Post	Pre	Post	Pre	Post
VO_{2max} (L/min)	3.58 ± 0.18	3.73 ± 0.22*	3.61 ± 0.22	3.63 ± 0.22	3.52 ± 0.38	3.87 ± 0.50 [†]
VO_{2max}(ml/kg/min)	55.2 ± 1.7	57.4 ± 2.3	56.1 ± 2.4	57.2 ± 2.5	53.3 ± 2.9	56.1 ± 3.9
VE_{max} (L/min)	109 ± 4	110 ± 5	109 ± 5	109 ± 5	108 ± 7	109 ± 12
HR max (bpm)	194 ± 2	194 ± 2	194 ± 2	196 ± 3	193 ± 4	192 ± 2
LT_{3.5mmol} (kph)	12.4 ± 0.3	13.2 ± 0.3*	12.2 ± 0.3	13.4 ± 0.6	12.9 ± 0.5	13.0 ± 0.3
Test Speed (kph)	12.3 ± 0.3	12.3 ± 0.3	12.0 ± 0.3	12.0 ± 0.3	12.6 ± 0.6	12.6 ± 0.4

* p<0.05 from pre to post-training in ALL. [†] p<0.05 percent change from pre-post differs between groups. All data are displayed as means ± SE

FIGURE 4.2 Absolute $\text{VO}_{2\text{max}}$ before and after training

* $p < 0.05$ from pre to post-training in ALL. † $p < 0.05$ percent change from pre-post differs between groups. All data are displayed as means \pm SE

TABLE 4.2. Submaximal cardiovascular and metabolic responses to treadmill exercise before and after training

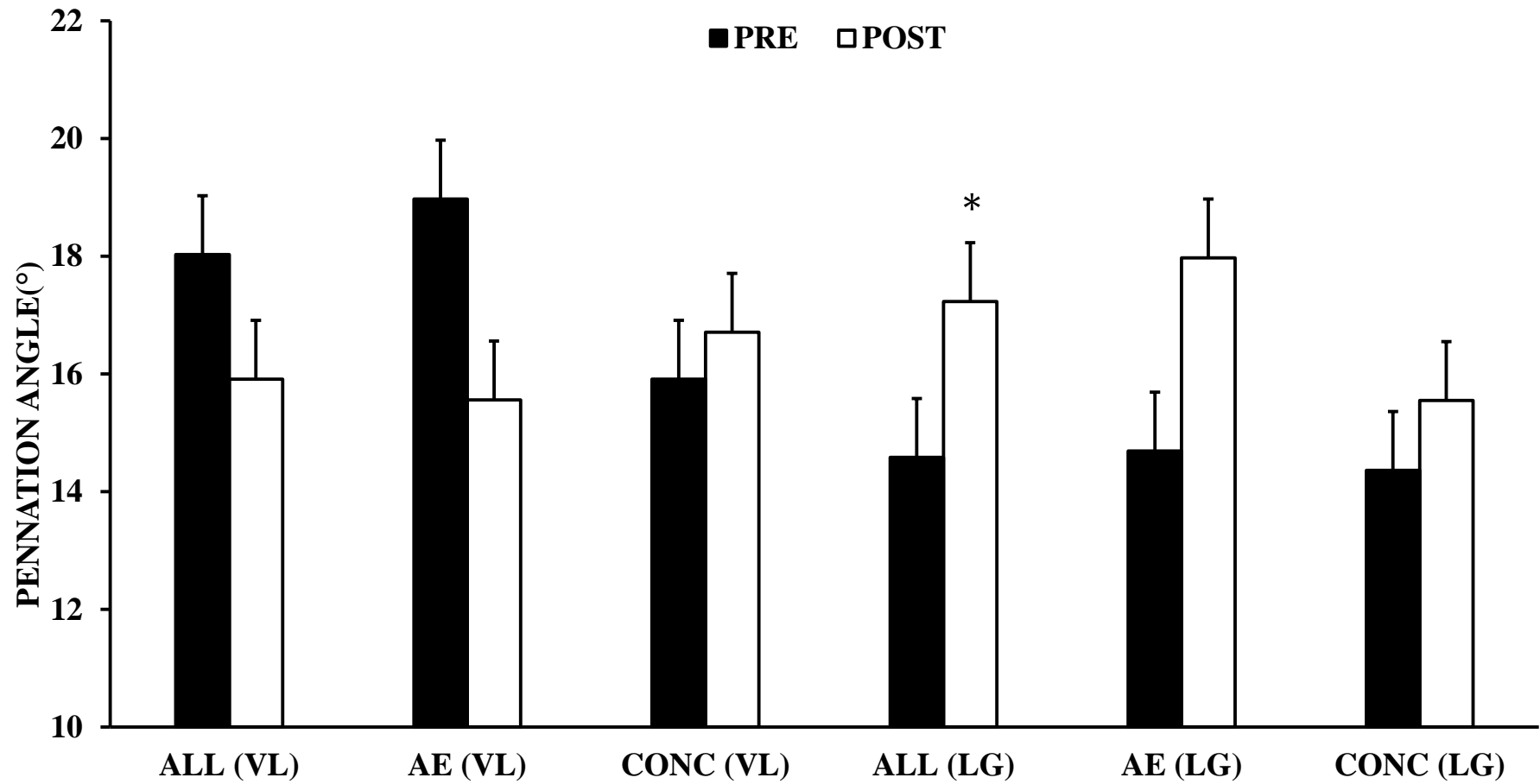
GROUP	ALL		AE		CONC	
	Pre	Post	Pre	Post	Pre	Post
VO₂ (L/min)	2.82 ± 0.14	2.86 ± 0.13	2.79 ± 0.15	2.83 ± 0.13	2.89 ± 0.37	2.94 ± 0.31
VO₂ (ml/kg/min)	43.8 ± 1.2	44.7 ± 1.4	43.8 ± 2.1	45.0 ± 2.0	43.8 ± 2.2	44.1 ± 1.9
VE (L/min)	69 ± 3	67 ± 3	66 ± 3	66 ± 4	73 ± 8	69 ± 6
RER	0.95 ± 0.01	0.92 ± 0.01*	0.94 ± 0.01	0.91 ± 0.01	0.97 ± 0.03	0.93 ± 0.02
HR (bpm)	176 ± 2	173 ± 3	177 ± 3	175 ± 4	175 ± 4	167 ± 4
RPE	12 ± 1	13 ± 1	12 ± 1	13 ± 1	13 ± 1	13 ± 1
Lactate (mmol/L)	2.63 ± 0.15	2.01 ± 0.19*	2.52 ± 0.21	1.88 ± 0.22	2.88 ± 0.07	2.49 ± 0.31
Test Speed(kph)	11.7 ± 0.3	11.7 ± 0.3	11.9 ± 0.3	11.9 ± 0.3	12.5 ± 0.6	12.5 ± 0.6

*p<0.05 pre to post-training in ALL. † p<0.05 percent change from pre- post differs between groups. All data are displayed as means ± SE

TABLE 4.3 Skeletal Muscle Architectural parameters before and after training in Vastus Lateralis and Lateral Gastrocnemius

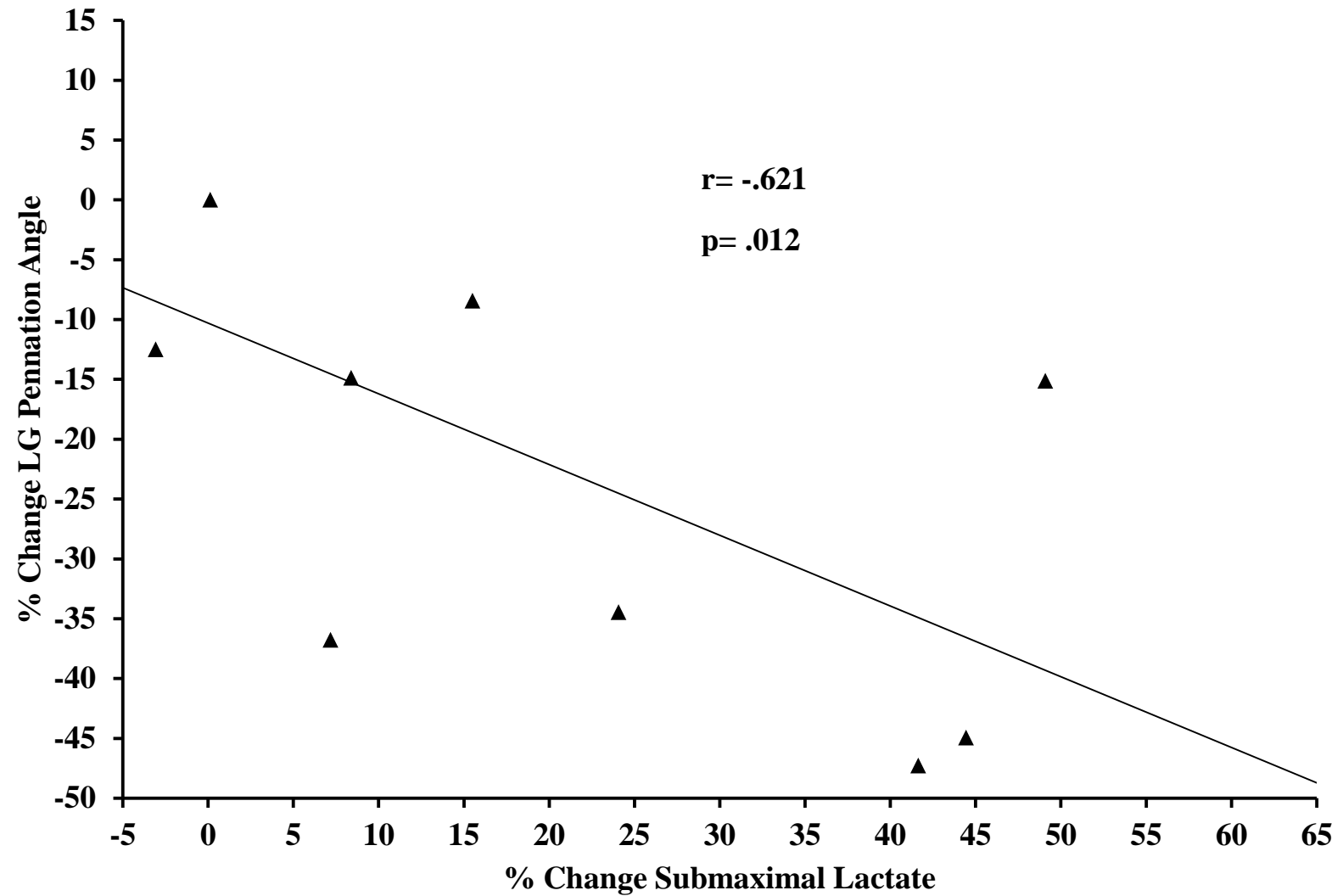
GROUP	ALL		AE		CONC	
	Pre	Post	Pre	Post	Pre	Post
VL Thickness (cm)	2.6 ± 0.1	2.6 ± 0.1	2.5 ± 0.1	2.6 ± 0.1	2.7 ± 0.1	2.6 ± 0.1
VL Angle	18 ± 1	16 ± 1	19 ± 1	16 ± 0 [†]	16 ± 0	17 ± 2
VL Fascicle Length (cm)	8.4 ± 0.5	9.5 ± 0.5	7.8 ± 0.6	9.6 ± 0.5	9.8 ± 0.2	9.3 ± 1.4
LG Thickness (cm)	1.3 ± 0.1	1.3 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.4 ± 0.1	1.4 ± 0.1
LG Angle	15± 1.0	17± 1.0*	15± 1	18 ± 1	14± 2	15± 1
LG Fascicle Length (cm)	5.1 ± 0.5	4.3 ± 0.3	4.9 ± 0.6	3.9 ± 0.2	5.6 ± 0.6	5.4 ± 0.7

VL= Vastus Lateralis LG=Lateral Gastrocnemius. *p<0.05 pre to post-training in ALL. [†] p<0.05 percent change from pre-post differs between groups. All data are displayed as means ± SE.

FIGURE 4.3 VL and LG pennation angle before and after training

* $p < 0.05$ from pre to post-training in ALL. † $p < 0.05$ percent change from pre-post differs between groups. All data are displayed as means \pm SE

FIGURE 4.4 Relationship between percent change in LG Pennation Angle and Submaximal Lactate Concentration



DISCUSSION

The current project was designed to determine whether concurrent circuit training influences cardiovascular and metabolic adaptations to marathon training in novice runners. In an attempt to expand the limited body of literature regarding architectural plasticity with aerobic training, we also examined the effect of concurrent training on skeletal muscle architecture. The most notable findings were that concurrent training enhanced absolute $\text{VO}_{2\text{max}}$ to a greater extent than run training alone, and that lateral gastrocnemius pennation angle was sensitive to prolonged endurance training. These findings suggest that it can be beneficial for beginning marathon runners to supplement with concurrent circuit-training programs.

The 5% increase in absolute $\text{VO}_{2\text{max}}$ is a well-documented adaptation to endurance training (7, 12, 15, 18, 37, 48, 52, 54, 57, 60), particularly in untrained individuals. There was no change in AE, and a 9% increase in absolute $\text{VO}_{2\text{max}}$ with CONC. The only study to examine the effects of concurrent circuit training on $\text{VO}_{2\text{max}}$ reported no further increase in $\text{VO}_{2\text{max}}$ beyond that observed with running only (19). The investigators used a similar circuit training program to the one utilized in the current study; however the repetitions were slightly lower (12-15 vs. 15-20). Circuit-training programs have been shown to improve both absolute and relative $\text{VO}_{2\text{max}}$ when performed on their own (20, 23, 31, 61). The circuit-training programs in the previously cited studies were nearly identical to the circuit-training program used in this investigation (23, 31, 61). The effects of the beginning marathon on absolute $\text{VO}_{2\text{max}}$ appear to be augmented by concurrent circuit-training.

By its nature, relative $\text{VO}_{2\text{max}}$ is a function of body weight, and is more likely to

improve as a result of both marked cardiovascular adaptation and decreases in body weight in less fit individuals. The initial relative $\text{VO}_{2\text{max}}$ of the subjects tested in previous isolated circuit training designs were much lower (31-37 ml/kg/min) compared with the initial levels of our subjects (55.2 ± 1.7 ml/kg/min, > 90th percentile). In addition, the initial training-induced gains in $\text{VO}_{2\text{max}}$ among unfit individuals result from increases in maximal stroke volume (54), which was not likely the case in the current study, as evidenced by the unchanged submaximal heart rate response observed with training, and the high initial fitness level of our subjects (48, 59). The lack of increase in relative $\text{VO}_{2\text{max}}$ could be explained by the fact that fit individuals tend to experience smaller gains in $\text{VO}_{2\text{max}}$ and are less likely to experience weight loss with training (48, 59). It is also possible that total training volume was too low to promote changes in relative $\text{VO}_{2\text{max}}$.

Lactate threshold (increased 5%) and lactate concentrations at submaximal intensities (decreased 22%) improved in ALL with training. Improvements in lactate threshold are commonly observed with prolonged endurance training, and the magnitude of change observed in the current study is similar to the 6-15% increase in lactate threshold reported by Saltin, Davis and Carter (12, 15, 48, 52). Lactate threshold and submaximal lactate responses were not influenced by training group. Circuit training alone has been shown to improve lactate threshold and submaximal lactate responses (16, 39). However, these studies lacked an aerobic or concurrent-training group and are difficult to compare to the current data. Like $\text{VO}_{2\text{max}}$, Saltin noted that the most marked improvements in lactate responses to given intensities were seen in individuals with the lowest initial fitness levels. While we did not report a further improvement in lactate threshold or submaximal lactate concentrations with concurrent training, this could be

explained by the high initial fitness level of our subjects, and by a small sample size. Additionally, it is possible that circuit-training does not deliver a sufficient overload stimulus to elicit further alterations in lactate metabolism.

No differences in running economy or fractional utilization (% $\text{VO}_{2\text{max}}$) were observed with training. The influence of beginning marathon-training programs on running economy is mixed (17, 38, 58). Trappe et al. reported a 7% increase in running economy, while Luden and Ferrauti both observed no change with beginning marathon training (38, 58). Recreational runners who ran 15-20 miles per week experienced no improvements in running economy with training, a volume identical with the initial stages of the current study (37). Although Scrimgeour et al. did not examine a training effect; the authors did report that runners who perform less than 60 km/wk tend to be less economical than runners who perform more than 60 km/wk (50). The peak mileage of the program utilized in the current study was 58 km (36 miles). It could be that 12-wks of training is too brief or that the training volume was too modest to measurably improve running economy. When combined with previous studies, our findings indicate that it is uncertain whether or not running economy will improve initially in recreational runners, particularly in response to beginning marathon training.

Vastus lateralis and lateral gastrocnemius muscle thickness and fascicle length were unaffected by the training, which is consistent with previous findings in our lab (Murach and Luden unpublished observations). While VL pennation angle generally increases with traditional resistance training (3, 5, 9, 51), no changes were observed with CONC, suggesting that concurrent endurance training may blunt the response, or that circuit training does not have the same effect as traditional resistance training. However,

this notion is not definitive, as there was no resistance-training group for comparison. LG pennation angle markedly increased (13%) in ALL with training, which is in line with our previous observations. LG pennation angle increases in response to endurance run training, bringing it closer in line with the architectural characteristics of distance runners (4).

Increased pennation angle could conceivably have implications both on the oxygen demand at a given work rate (running economy) and the metabolic turnover associated with the intensity (lactate production), thereby decreasing fatigueability. The lack of change in running economy with training indicates that the increase in LG pennation angle did not influence oxidative energy expenditure. However, fascicles of pennate muscles rotate during dynamic muscle contraction, which promotes optimal actin and myosin overlap for any given magnitude of whole muscle shortening/lengthening (9). Interestingly, the extent of rotation is amplified with increasing pennation angles (39). Shorter fascicle excursion for a given degree of whole muscle shortening/lengthening may result in optimal actin/myosin overlap, which increases the force producing capabilities of each fiber. If a given fiber can produce more force and power during each contraction, this theoretically reduces stress from other fibers; and given the principle of orderly recruitment, these fibers are presumably fast-twitch fibers. We did indeed observe an inverse relationship ($r = -.621$; $p = .012$) between changes in LG pennation angle, and changes in submaximal lactate concentrations in ALL. This may suggest that as exercise duration progressively increases, the attenuated fascicle excursions of each contraction may serve to reduce the need to recruit fast-twitch muscle fibers, decreasing lactate production, and potentially decrease fatigueability.

The concurrent training regiment utilized in the current study was similar to both beginning marathon and circuit-training programs that have successfully improved $\text{VO}_{2\text{max}}$ when performed on their own. We did not observe a further improvement in lactate responses or running economy, which both may be due to the high initial fitness level of our subjects and a small sample size. Marathon training is likely to alter LG pennation angle in a fashion that may support the ability to run long distances, bringing architectural characteristics closer in line with the profile of trained distance runners. Given the small sample size, it is unclear whether these adaptations are altered through concurrent resistance training. Notwithstanding these limitations, the current data provide preliminary evidence that it may be worthwhile to add circuit training to a marathon-training program. Further research is required to confirm our findings and to provide more complete insight into the potential for concurrent circuit training to enhance the training adaptations elicited by run training.

CHAPTER FIVE

SUMMARY

The primary aims of this study were to evaluate the effect of concurrent circuit and beginning marathon training on $\text{VO}_{2\text{max}}$, lactate threshold, running economy and skeletal muscle architecture using a cross sectional design. We hypothesized that compared to running alone concurrent circuit training would influence: 1) $\text{VO}_{2\text{max}}$, 2) lactate threshold, 3) running economy and 4) skeletal muscle architecture.

In line with our hypotheses, concurrent circuit training did improve absolute $\text{VO}_{2\text{max}}$, with no change in relative $\text{VO}_{2\text{max}}$. Contrary to our hypothesis, concurrent circuit training had no effect on lactate threshold (which improved in ALL) or running economy when compared to running alone. There was a significant increase in LG pennation angle in ALL (consistent with previous findings in our lab), with no difference between AE and CONC. Some possible explanations for a lack of efficacy include, but are not limited to a small sample size (CONC $n=4$), unsupervised marathon training, and no prescription of running intensities. Notwithstanding these limitations, our findings indicate that it may be beneficial for beginning marathon runners to concurrently circuit train (due to enhanced cardiovascular adaptation), and that LG pennation angle increases following endurance training.

Appendix I

James Madison University Department of Kinesiology Informed Consent

Marathon Training Subjects

Purpose

You are being asked to volunteer for a study conducted by Dr. Todd, Dr. Luden, Nicole Hafner and Cory Greever titled “Aerobic, skeletal muscle, and vascular adaptations to marathon run training with and without concurrent resistance training”. The primary aims of this study are to determine if marathon training alters the diameter and thickness of the vessels in your neck (carotid), arm (brachial) and leg (popliteal), blood flow mechanics in your brachial and popliteal arteries, skeletal muscle architecture (shape and size) of your calf and thigh, and your cardiovascular physiology.

Experimental Procedures

You will be asked to report to James Madison University’s Human Performance Laboratory (Godwin 209) on three occasions. Specifically, you will be asked to report to the laboratory twice at the beginning of the marathon-training program, and once more towards the end of the marathon-training program. Visits 1 (1 hr) and 2 (1.5 hrs) will take a combined 2.5 hrs and visit 3 will require 2 hrs, for a total time commitment of approximately 4.5 hrs. Detailed information for each of these trials is provided below:

Visit 1 – Week of September 12th

Prior to any data collection, you will be asked to complete a health history questionnaire to ensure that you meet the study criteria and that you do not have any risk factors that would prevent you from performing heavy exercise, although this is unlikely due to your participation in the GKIN 100-marathon class. In the process of filling out these forms, you will be asked to share information regarding your general health and lifestyle with the researchers. If you meet the criteria for the study, the researchers will measure your height and weight and you will be asked to fill out the International Physical Activity Questionnaire (IPAQ). The IPAQ is used to measure time spent sitting, walking, performing moderate activity and vigorous activity. You will also be asked to abide by some guidelines concerning vitamin supplementation, medication use, caffeine use, previous exercise and fasted state so that measurements obtained are the most accurate (see attached form). Lastly, you will be asked to fill out a form ranking how often you eat certain foods. The purpose of this is because some foods eaten often can have affects on the vascular system.

Then, to familiarize you with the vascular assessment procedures, you will be asked to undergo an ultrasound and flow mediation dilation evaluation of your brachial artery. This non-invasive procedure involves lying down and relaxing in a cool dark room while the investigator images the artery using a 5-10 MHz ultrasound scanner (Mindray DC-6). Once the image is saved a flow mediated dilation measurement will be taken. This involves the placement of a blood pressure cuff distal to the artery being imaged and inflated to 250 mmHg for 5 minutes. After this time, the cuff will be deflated and measurements of dilation will be recorded for 2 minutes.

Following the vascular familiarization trial, you will be asked to undergo a DEXA scan for measures of body composition (percent body fat, lean body mass, and bone mineral density). You will be asked to lie on your back completely still, while breathing normally and closing your eyes while the scan is in progress. The entire scan lasts approximately 6 minutes.

Finally, you will be asked to perform a muscle function test. Following a 5-minute treadmill warm-up at a self-selected walking speed, you will be positioned in a custom-built leg extension machine equipped with a force transducer. When prompted, you will perform a maximal leg extension against the padded stationary leg extension bar. The force produced by you will be processed by the transducer, recorded, and stored in a computer for analysis.

Visit 2 – Week of September 12th

At least 24 hrs following visit 1, you will be asked to report to the laboratory for visit 2, in which you will be asked to perform a treadmill test and measures of vascular physiology and skeletal muscle architecture. Upon reporting to the lab, you will be asked to lie down and relax in a cool dark room while the investigator images your arteries (neck, leg, and arm) using the ultrasound scanner. Once the image is saved, a flow mediated dilation measurement will be taken. This involves the placement of a blood pressure cuff distal to the artery being imaged and inflated to 250 mmHg for 5 minutes. After this time, the cuff will be deflated and measurements of dilation will be recorded for 2 minutes. Immediately following the vascular assessment, ultrasound measurements of your vastus lateralis (outside quadriceps muscle) and lateral gastrocnemius (outside calf muscle) will be obtained. This will require you to stand upright with muscles relaxed while the investigator identifies and scans the two muscles using a 5-10 MHz ultrasound scanner (Mindray DC-6). Once the ultrasound is complete, upon your permission, investigators will mark the ultrasound sites with a medical grade pen. This marking is important because it will identify the exact sites to be used for the post-measurement. There will not be any negative consequences if you prefer not to have the marks on your legs.

Immediately following the ultrasound measurements, you will be asked to perform a treadmill running test. The test is designed to assess your cardiovascular fitness. To do this, the initial treadmill speed will be subjectively determined during a self-selected 5-minute warm-up. You will be instructed to select a speed that you could maintain during a prolonged run of “easy to moderate” intensity. Following the warm-up you will run at this pace for 3-minutes. You will then dismount the treadmill and a drop of blood will be obtained through a finger lancet and analyzed for blood lactate during a 1-minute rest period. These 3-minute stages will continue (estimate approximately 6-8 samples), increasing .4 mph in speed, until you have exceeded your lactate threshold (moderate to vigorous intensity). The treadmill speed that elicits your lactate threshold will then stay constant and the treadmill grade will increase 2 percent every 2 minutes until you request to stop or are unable to continue running. The test is no more vigorous than what you will perform during their marathon training intervention.

Metabolic measurements such as oxygen uptake and ventilation will be measured during the treadmill test using a metabolic cart. To do this, you will be asked to breathe through a mouthpiece/breathing apparatus that collects your expired breath during the entire duration of the test. You will also be asked to provide subjective ratings of your exertion level at various time points throughout the exercise protocol. You will do this by pointing to your corresponding level of exertion (rated numerically from 6-20) on a Borg RPE scale. Your heart rate will also be measured using a Polar heart rate monitor that will be worn around your chest during each exercise session.

Visit 3 – Week of November 28th

You will be asked to return to the laboratory to complete post-measures of IPAQ, DEXA, food intake form, FMD checklist, ultrasonography (vascular physiology including flow mediated dilation and skeletal muscle architecture), muscle strength test, and treadmill testing.

Risks

Ultrasonography: Ultrasonography is a non-invasive and risk-free procedure. There are no known adverse effects.

Treadmill Testing: According to the American College of Sports Medicine’s Guidelines for Exercise Testing and Prescription, the risk associated with maximal testing for individuals categorized as “low risk” is very minimal, and physician supervision and approval is not necessary. The conditions that the exercise sessions are to take place are likely safer than your typical exercise environment. If you do not meet the ACSM criteria for “low risk”, you will not be permitted to participate in the study. A physician will be available by pager if the need for medical attention arises throughout the study period. In the unlikely event of cardiac or other complications during exercise, an emergency plan is in place. This includes immediate access to a phone to call emergency personnel. In addition, at least one of the listed investigators will be

present during all exercise sessions, and all are CPR certified. The exercise protocol may result in minor-moderate levels of muscle soreness and fatigue for 1-2 days following each exercise session. Since running is a largely eccentric exercise it is possible that you will experience soreness for up to 48 hours post exercise. It should be mentioned though that the test is no more rigorous than what you will be performing during the marathon training intervention and the risk for soreness is minimal.

Finger Stick Blood Sampling: The risks associated with obtaining small samples of blood via finger-sticks are minimal but include bruising and discomfort for 24 to 48 hours and infection. The risk for infection is small and will be minimized by the use of sterile methods, including the use of sterile alcohol pads, sterile gauze, and band-aids.

Muscle Strength Testing: The risks of muscle strength testing include soreness from exertion 24-72 hours post and potential lightheadedness or loss of consciousness if correct breathing technique is not utilized. These risks will be minimized by instructing and emphasizing proper breathing technique.

Flow Mediated Dilation: The risks of flow mediated dilation measurements include discomfort often described as your arm or leg is “falling asleep”; there is a temporary reduction or loss of feeling because the vessel is occluded for 5 minutes.

DEXA: The risk of DEXA is exposure to low dose radiation associated with the x-ray scan. According to the manufacturer’s specifications, whole body DEXA analysis exposes participants to 1.5 mrem of radiation. The exposure to radiation during a single chest x-ray is more than 3 times greater than radiation from DEXA. Also, background radiation from DEXA is about equal to the amount of radiation one experiences during a flight from New York to London. If you are pregnant or think you may be pregnant, you should **not** participate in the DEXA scan. Further, the effects of radiation are accumulative. Thus, if you are concerned about your previous levels of radiation exposure, please communicate these concerns with the investigative team.

Benefits

You will receive a free VO₂max assessment and body composition assessment (DEXA), which includes measures of percent body fat, lean mass and bone mineral density. In addition, you will gain valuable information about your movement efficiency, muscle physiology, and vascular health. This knowledge may aid your training and performance. Participation in this novel research project will also contribute to our understanding of physiological adaptation to marathon training with and without concurrent RE.

Inquiries

If you have any questions or concerns during the time of your participation in this study, or after its completion or you would like to receive a copy of the final aggregate results of this study, please contact Nicole Hafner at hafnernm@dukes.jmu.edu or Cory Greever at greev2cj@dukes.jmu.edu. In the case of any immediate concerns or adverse reactions during the study, call Dr. Luden at (540) 568-4069 or Dr. Todd at (540) 209-2001.

Confidentiality

The results of this research project will be presented at regional and national conferences and in peer-reviewed exercise science journals. All data and results will be kept confidential. You will be assigned an identification code. At no time will your name be identified with your individual data. The researcher retains the right to use and publish non-identifiable data. All de-identified data will be kept secured in a locked cabinet and will remain there indefinitely. Final aggregate results will be made available to participants upon request.

Freedom of Consent

Your participation is entirely voluntary. Your decision to participate or not will not have any influence on your GKIN 100 grade or alter your standing in the class. Should you choose to participate, you can withdraw at any time without consequences of any kind.

Questions about Your Rights as a Research Subject

Dr. David Cockley

Chair, Institutional Review Board

James Madison University
(540) 568-2834
cocklede@jmu.edu

Giving of Consent

I have read this consent form and I understand what is being requested of me as a participant in this study. I freely consent to participate. I have been given satisfactory answers to my questions. The investigator provided me with a copy of this form. I certify that I am at least 18 years of age.

Name of Subject (Printed)

Name of Researcher (Printed)

Name of Subject (Signed)

Name of Researcher (Signed)

Date

Date

Appendix II

James Madison University Department of Kinesiology Informed Consent Marathon- and Resistance Training Subjects

Purpose

You are being asked to volunteer for a study conducted by Dr. Todd, Dr. Luden, Nicole Hafner and Corey Greever titled “Aerobic, skeletal muscle, and vascular adaptations to marathon run training with and without concurrent resistance training”. The primary aims of this study are to determine if marathon training alters the diameter and thickness of the vessels in your neck (carotid), arm (brachial) and leg (popliteal), blood flow mechanics in your brachial and popliteal arteries, skeletal muscle architecture (shape and size) of your calf and thigh, and your cardiovascular physiology.

Experimental Procedures

You will be asked to report to James Madison University’s Human Performance Laboratory (Godwin 209) on three occasions. Specifically, you will be asked to report to the laboratory twice at the beginning of the marathon-training program, and once more towards the end of the marathon-training program. Visits 1 (1 hr) and 2 (1.5 hrs) will take a combined 2.5 hrs and visit 3 will require 2 hrs, for a total time commitment of approximately 4.5 hrs.

As part of the resistance training group you will also be asked to participate in 3 resistance training sessions, 3 days per week for 9 weeks. Each training session will last about 45 minutes. The total time commitment for the resistance training sessions is about 20 hours and 15 minutes.

The combined total time for the experimental testing and the resistance training will be approximately 25 hours.

Detailed information for each of these trials is provided below:

Visit 1 – Week of September 12th

Prior to any data collection, you will be asked to complete a health history questionnaire to ensure that you meet the study criteria and that you do not have any risk factors that would prevent you from performing heavy exercise, although this is unlikely due to your participation in the GKin 100-marathon class. In the process of filling out these forms, you will be asked to share information regarding your general health and lifestyle with the researchers. If you meet the criteria for the study, the researchers will measure your height and weight and you will be asked to fill out the International Physical Activity Questionnaire (IPAQ). The IPAQ is used to measure time spent sitting, walking, performing moderate activity and vigorous activity. You will also be asked to abide by some guidelines concerning vitamin supplementation, medication use, caffeine use, previous exercise and fasted state so that measurements obtained are the most accurate (see attached form). Lastly, you will be asked to fill out a form ranking how often you eat certain foods. The purpose of this is because some foods eaten often can have affects on the vascular system.

Then, to familiarize you with the vascular assessment procedures, you will be asked to undergo an ultrasound and flow mediated dilation evaluation of your brachial artery. This non-invasive procedure involves lying down and relaxing in a cool dark room while the investigator images the artery using a 5-10 MHz ultrasound scanner (Mindray DC-6). Once the image is saved a flow mediated dilation measurement will be taken. This involves the placement of a blood pressure cuff distal to the artery being imaged and inflated to 250 mmHg for 5 minutes. After this time, the cuff will be deflated and measurements of dilation will be recorded for 2 minutes.

Following the vascular familiarization trial, you will be asked to undergo a DEXA scan for measures of body composition (percent body fat, lean body mass, and bone mineral density). You will be asked to lie on

your back completely still, while breathing normally and closing your eyes while the scan is in progress. The entire scan lasts approximately 6 minutes.

Finally, you will be asked to perform a muscle function test. Following a 5-minute treadmill warm-up at a self-selected walking speed, you will be positioned in a custom-built leg extension machine equipped with a force transducer. When prompted, you will perform a maximal leg extension against the padded stationary leg extension bar. The force produced by you will be processed by the transducer, recorded, and stored in a computer for analysis.

Visit 2 – Week of September 12th

At least 24 hrs following visit 1, you will be asked to report to the laboratory for visit 2, in which you will be asked to perform a treadmill test and measures of vascular physiology and skeletal muscle architecture. Upon reporting to the lab, you will be asked to lie down and relax in a cool dark room while the investigator images your arteries (neck, leg, and arm) using the ultrasound scanner. Once the image is saved, a flow mediated dilation measurement will be taken. This involves the placement of a blood pressure cuff distal to the artery being imaged and inflated to 250 mmHg for 5 minutes. After this time, the cuff will be deflated and measurements of dilation will be recorded for 2 minutes. Immediately following the vascular assessment, ultrasound measurements of your vastus lateralis (outside quadriceps muscle) and lateral gastrocnemius (outside calf muscle) will be obtained. This will require you to stand upright with muscles relaxed while the investigator identifies and scans the two muscles using a 5-10 MHz ultrasound scanner (Mindray DC-6). Once the ultrasound is complete, upon your permission, investigators will mark the ultrasound sites with a medical grade pen. This marking is important because it will identify the exact sites to be used for the post-measurement. There will not be any negative consequences if you prefer not to have the marks on your legs.

Immediately following the ultrasound measurements, you will be asked to perform a treadmill running test. The test is designed to assess your cardiovascular fitness. To do this, the initial treadmill speed will be subjectively determined during a self-selected 5-minute warm-up. You will be instructed to select a speed that you could maintain during a prolonged run of “easy to moderate” intensity. Following the warm-up you will run at this pace for 3-minutes. You will then dismount the treadmill and a drop of blood will be obtained through a finger lancet and analyzed for blood lactate during a 1-minute rest period. These 3-minute stages will continue (estimate approximately 6-8 samples), increasing .4 mph in speed, until you have exceeded your lactate threshold (moderate to vigorous intensity). The treadmill speed that elicits your lactate threshold will then stay constant and the treadmill grade will increase 2 percent every 2 minutes until you request to stop or are unable to continue running. The test is no more vigorous than what you will perform during their marathon training intervention

Metabolic measurements such as oxygen uptake and ventilation will be measured during the treadmill test using a metabolic cart. To do this, you will be asked to breathe through a mouthpiece/breathing apparatus that collects your expired breath during the entire duration of the test. You will also be asked to provide subjective ratings of your exertion level at various time points throughout the exercise protocol. You will do this by pointing to your corresponding level of exertion (rated numerically from 6-20) on a Borg RPE scale. Your heart rate will also be measured using a Polar heart rate monitor that will be worn around your chest during each exercise session.

Visit 3 – Week of November 28th

You will be asked to return to the laboratory to complete post-measures of IPAQ, DEXA, food intake form, FMD checklist, ultrasonography (vascular physiology including FMD and skeletal muscle architecture), muscle strength test, and treadmill testing.

Resistance Training

You have volunteered to participate in the resistance training intervention. This requires that you complete 2 supervised and 1 unsupervised resistance training session per week, for 9 weeks (wks 9.26.11 to

11.21.11). In the first week of the intervention, the 2 supervised sessions will be familiarization sessions, in which you will become acclimated to the training protocol, proper form, and correct beginning resistance levels for each exercise. Each supervised session will take place in Godwin 116 and/or 218 using resistance exercise machines. Each supervised session will be facilitated by trained individual(s). Each session will consist of 10 total machine exercises (6 lower body, 4 upper body) and 2 core exercises (i.e. crunches/sit-ups), which will be preceded by a 5-minute self selected warm-up. You will perform 3 sets of maximum repetitions for each machine and core exercise. Each set will be timed and will last 40 seconds, with each set separated by 20 seconds of passive rest. For machine exercises, you should be able to complete 15-20 repetitions in the 40-second time-period. If you complete more than 20 repetitions on 2 consecutive sets, the resistance will be raised accordingly on the subsequent set. If you are unable to complete 15 repetitions with correct form on any 1 set, the resistance will be lowered accordingly on the subsequent set. You will be required to replicate this workout on your own once per week, with the exception of the strict timing between each set. Specifically, you will be required to complete 3 sets of 15 repetitions for each exercise. Each session will last approximately 45 minutes, for a total training time commitment of 20 hrs and 15 min. Training sessions will take place according to your schedule and weight room availability.

Risks

Ultrasonography: Ultrasonography is a non-invasive and risk-free procedure. There are no known adverse effects.

Treadmill Testing: According to the American College of Sports Medicine's Guidelines for Exercise Testing and Prescription, the risk associated with maximal testing for individuals categorized as "low risk" is very minimal, and physician supervision and approval is not necessary. The conditions that the exercise sessions are to take place are likely safer than your typical exercise environment. If you do not meet the ACSM criteria for "low risk", you will not be permitted to participate in the study. A physician will be available by pager if the need for medical attention arises throughout the study period. In the unlikely event of cardiac or other complications during exercise, an emergency plan is in place. This includes immediate access to a phone to call emergency personnel. In addition, at least one of the listed investigators will be present during all exercise sessions, and all are CPR certified. The exercise protocol may result in minor-moderate levels of muscle soreness and fatigue for 1-2 days following each exercise session. Since running is a largely eccentric exercise it is possible that you will experience soreness for up to 48 hours post exercise. It should be mentioned though that the test is no more rigorous than what you will be performing during the marathon training intervention and the risk for soreness is minimal.

Finger Stick Blood Sampling: The risks associated with obtaining small samples of blood via fingersticks are minimal but include bruising and discomfort for 24 to 48 hours and infection. The risk for infection is small and will be minimized by the use of sterile methods, including the use of sterile alcohol pads, sterile gauze, and band-aids.

Muscle Strength Testing: The risks of muscle strength testing include soreness from exertion 24-72 hours post and potential lightheadedness or loss of consciousness if correct breathing technique is not utilized. These risks will be minimized by instructing and emphasizing proper breathing technique.

Flow Mediated Dilation: The risks of FMD measurements include discomfort often described as your arm or leg is "falling asleep"; there is a temporary reduction or loss of feeling because the vessel is occluded for 5 minutes.

DEXA: The risk of DEXA is exposure to low dose radiation associated with the x-ray scan. According to the manufacturer's specifications, whole body DEXA analysis exposes participants to 1.5 mrem of radiation. The exposure to radiation during a single chest x-ray is more than 3 times greater than radiation from DEXA. Also, background radiation from DEXA is about equal to the amount of radiation one experiences during a flight from New York to London. If you are pregnant or think you may be pregnant, you should **not** participate in the DEXA scan. Further, the effects of radiation are accumulative. Thus, if you are concerned about your previous levels of radiation exposure, please communicate these concerns with the investigative team.

Resistance Training: According to the American College of Sports Medicine's Guidelines for Exercise Testing and Prescription, the risk associated with resistance training for individuals categorized as "low risk" is very minimal, and physician supervision and approval is not necessary. If you do not meet the ACSM criteria for "low risk", you will not be permitted to participate in the resistance exercise portion of the study. Resistance training may result in muscle soreness. There is a risk of musculoskeletal injury due to improper form and loading. These risks will be minimized by demonstrating proper form for each exercise and proper load progressions during the first 3 resistance training sessions, which will be used for familiarization purposes. To promote safety during unsupervised sessions, visual aids will be provided for each exercise with form instructions and general resistance training guidelines.

Benefits

You will receive a free VO2max assessment and body composition assessment (DEXA), which includes measures of percent body fat, lean mass and bone mineral density. In addition, you will gain valuable information about your movement efficiency, muscle physiology, and vascular health. This knowledge may aid your training and performance. Participation in this novel research project will also contribute to our understanding of physiological adaptation to marathon training with and without concurrent RE.

Inquiries

If you have any questions or concerns during the time of your participation in this study, or after its completion or you would like to receive a copy of the final aggregate results of this study, please contact Nicole Hafner at hafnernm@dukes.jmu.edu or Cory Greever at greev2cj@dukes.jmu.edu. In the case of any immediate concerns or adverse reactions during the study, call Dr. Luden at (540) 568-4069 or Dr. Todd at (540) 209-2001.

Confidentiality

The results of this research project will be presented at regional and national conferences and in peer-reviewed exercise science journals. All data and results will be kept confidential. You will be assigned an identification code. At no time will your name be identified with your individual data. The researcher retains the right to use and publish non-identifiable data. All de-identified data will be kept secured in a locked cabinet and will remain there indefinitely. Final aggregate results will be made available to participants upon request.

Freedom of Consent

Your participation is entirely voluntary. Your decision to participate or not will not have any influence on your GKIN 100 grade or alter your standing in the class. Should you choose to participate, you can withdraw at any time without consequences of any kind.

Questions about Your Rights as a Research Subject

Dr. David Cockley

Chair, Institutional Review Board

James Madison University

(540) 568-2834

cocklede@jmu.edu

Giving of Consent

I have read this consent form and I understand what is being requested of me as a participant in this study. I freely consent to participate. I have been given satisfactory answers to my questions. The investigator provided me with a copy of this form. I certify that I am at least 18 years of age.

Name of Subject (Printed)

Name of Researcher (Printed)

Name of Subject (Signed)

Name of Researcher (Signed)

Date

Date

Appendix III

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (October 2002)

Long Form: Last 7 Days, Self-Administered Format
FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health-related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ

Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation

Translation from English is encouraged to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

Further Developments of IPAQ

International collaboration on IPAQ is on-going and an *International Physical Activity Prevalence Study* is in progress. For further information see the IPAQ website.

More Information

More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective*. Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** and **moderate** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.

PART 1: JOB-RELATED PHYSICAL ACTIVITY

The first section is about your work. This includes paid jobs, farming, volunteer work, course work, and any other unpaid work that you did outside your home. Do not include unpaid work you might do around your home, like housework, yard work, general maintenance, and caring for your family. These are asked in Part 3.

1. Do you currently have a job or do any unpaid work outside your home?

☐

Yes

☐

No



Skip to PART 2: TRANSPORTATION

The next questions are about all the physical activity you did in the **last 7 days** as part of your paid or unpaid work. This does not include traveling to and from work.

2. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, heavy construction, or climbing up stairs **as part of your work**? Think about only those physical activities that you did for at least 10 minutes at a time.

_____ **days per week**

☐

No vigorous job-related physical activity



Skip to question 4

3. How much time did you usually spend on one of those days doing **vigorous** physical activities as part of your work?

hours per day

minutes per day

4. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads **as part of your work**? Please do not include walking.

_____ **days per week**

☐

No moderate job-related physical activity



Skip to question 6

5. How much time did you usually spend on one of those days doing **moderate** physical activities as part of your work?

hours per day

minutes per day

6. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **as part of your work**? Please do not count any walking you did to travel to or from work.

_____ **days per week**

☐

No job-related walking



Skip to PART 2: TRANSPORTATION

7. How much time did you usually spend on one of those days **walking** as part of your work?

_____ **hours per day**
 _____ **minutes per day**

PART 2: TRANSPORTATION PHYSICAL ACTIVITY

These questions are about how you traveled from place to place, including to places like work, stores, movies, and so on.

8. During the **last 7 days**, on how many days did you **travel in a motor vehicle** like a train, bus, car, or tram?

_____ **days per week**

☐

No traveling in a motor vehicle



Skip to question 10

9. How much time did you usually spend on one of those days **traveling** in a train, bus, car, tram, or other kind of motor vehicle?

_____ **hours per day**
 _____ **minutes per day**

Now think only about the **bicycling** and **walking** you might have done to travel to and from work, to do errands, or to go from place to place.

10. During the **last 7 days**, on how many days did you **bicycle** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐

No bicycling from place to place



Skip to question 12

11. How much time did you usually spend on one of those days to **bicycle** from place to place?

_____ **hours per day**
 _____ **minutes per day**

12. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐

No walking from place to place



*Skip to PART 3:
 HOUSEWORK, HOUSE
 MAINTENANCE, AND
 CARING FOR FAMILY*

13. How much time did you usually spend on one of those days **walking** from place to place?

_____ **hours per day**

_____ **minutes per day**

PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

This section is about some of the physical activities you might have done in the **last 7 days** in and around your home, like housework, gardening, yard work, general maintenance work, and caring for your family.

14. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, chopping wood, shoveling snow, or digging **in the garden or yard**?

_____ **days per week**

☐

No vigorous activity in garden or yard



Skip to question 16

15. How much time did you usually spend on one of those days doing **vigorous** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

16. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, sweeping, washing windows, and raking **in the garden or yard**?

_____ **days per week**

☐

No moderate activity in garden or yard



Skip to question 18

17. How much time did you usually spend on one of those days doing **moderate** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

18. Once again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, washing windows, scrubbing floors and sweeping **inside your home**?

_____ **days per week**

☐

No moderate activity inside home



***Skip to PART 4:
RECREATION, SPORT AND
LEISURE-TIME PHYSICAL
ACTIVITY***

19. How much time did you usually spend on one of those days doing **moderate** physical activities inside your home?

_____ **hours per day**
_____ **minutes per day**

PART 4: RECREATION, SPORT, AND LEISURE-TIME PHYSICAL ACTIVITY

This section is about all the physical activities that you did in the **last 7 days** solely for recreation, sport, exercise or leisure. Please do not include any activities you have already mentioned.

20. Not counting any walking you have already mentioned, during the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **in your leisure time**?

_____ **days per week**

☐

No walking in leisure time



Skip to question 22

21. How much time did you usually spend on one of those days **walking** in your leisure time?

_____ **hours per day**
_____ **minutes per day**

22. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like aerobics, running, fast bicycling, or fast swimming **in your leisure time**?

_____ **days per week**

☐

No vigorous activity in leisure time



Skip to question 24

23. How much time did you usually spend on one of those days doing **vigorous** physical activities in your leisure time?

_____ **hours per day**
_____ **minutes per day**

24. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like bicycling at a regular pace, swimming at a regular pace, and doubles tennis **in your leisure time**?

_____ **days per week**

☐

No moderate activity in leisure time



Skip to PART 5: TIME SPENT SITTING

25. How much time did you usually spend on one of those days doing **moderate** physical activities in your leisure time?

_____ **hours per day**
_____ **minutes per day**

PART 5: TIME SPENT SITTING

The last questions are about the time you spend sitting while at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television. Do not include any time spent sitting in a motor vehicle that you have already told me about.

26. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekday**?

_____ **hours per day**

_____ **minutes per day**

27. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekend day**?

_____ **hours per day**

_____ **minutes per day**

This is the end of the questionnaire, thank you for participating

*Appendix IV***Please Complete the Following:**

Sex: Male Female (circle one)

Age (yrs):

Height (inches):

Weight (lbs):

Average Exercise Habits over the Past 3 Months:

Avg. # days of exercise per week:

Avg. # of days of aerobic exercise per week:

Do you have a muscle or joint injury that precludes the completion of the exercise protocol?

References

1. Aagard P and Andersen JL. Effects of strength training in endurance athletes. *Sc J Med Sci Sp*: 20: p.39-47, 2010.
2. Aagard P. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol*: 534(2): p.613-623, 2001.
3. Abe T, DeHoyos DV, Pollock ML, and Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. *Eur J Appl Physiol*: 81(3): p.174-180, 2000.
4. Abe T, Kumagai K, and Brechue WF. Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sp Ex*: 32(6): p.1125-1129, 2000.
5. Alegre LM, Jimenez F, Gonzalo-Orden JM, Martin-Acero R, and Aguado X. Effects of dynamic resistance training on fascicle length and isometric strength. *J Sports Sci*: 24(5): p.501-8, 2006.
6. Bell GJ et al. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol*: 81(5): p.418-427, 2000.
7. Billat VL et al. Interval training at $\text{VO}_{2\text{max}}$ effects on aerobic performance and overtraining markers. *Med Sci Sp Ex*: 31(1): p.156-163, 1999.
8. Bishop, D. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sp Ex*: 31(6): p.886, 1999.
9. Blazeovich AJ. Training-specific muscle architecture adaptation after 5-wk training in athletes *Med Sci Sp Ex*: 35(12): p.2013, 2003.
10. Bouchard, C et al. Aerobic performance in brothers, dizygotic and monozygotic twins. *Med Sci Sp Ex*: 18(6): p.639-646, 1986.
11. Campos GE, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur J Appl Physiol*: 88(1-2): p.50-60, 2002.
12. Carter C, Jones AM, Doust JH. Effects of 6 weeks of endurance training on the lactate minimum speed. *J Sport Sci*: 17: p.957-967, 1999.
13. Costill DL, Thomason H and Roberts E. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sp*: 5: p.248-52, 1973.
14. Cullinen K, Caldwell M. Weight training increases fat-free mass and strength in untrained young women. *J Am Diet Assoc*: 98(4): p.414-8, 1998.
15. Davis JA, Frank MH, Whipp BJ and Wasserman K. Anaerobic threshold alterations caused by endurance training in middle aged men. *J Appl Physiol*: 46(6): p.1039-1046, 1979.
16. Edge JJ. Effects of resistance training on H regulation, buffer Capacity, and repeated sprints. *Med Sci Sp Ex*: 38(11): p. 2004-2011, 2006.
17. Ferrauti A, Bergermann M and Fernandez-Fernandez J. Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. *J Str Con*: 24(10): p. 2770-2778, 2010.
18. Franch J, Madsen K, Djurhuus MS, Pedersen PK. Improved running economy following intensified training correlates with reduced ventilatory demands. *Med Sci Sp Ex*: 30(8): p. 1250-1256, 1998.

19. Gettman LR. The effect of circuit weight training on strength, cardiorespiratory function, and body composition of adult men *Med Sci Sp*: 10(3): p. 171, 1978.
20. Gettman LR. A comparison of combined running and weight training with circuit weight training. *Med Sci Sp Ex*: 14(3): p. 229, 1982.
21. Girandola RN and Katch V. Effects of nine weeks of physical training on aerobic capacity and body composition in college man. *Arch Phys Med Rehab*: 54(11): p. 521-524, 1973.
22. Goreham C, Green HJ, Ball-Burnett M, Ranney D. High-resistance training and muscle metabolism during prolonged exercise. *Am J Physiol Endocrinol Metab*: 276:489-496, 1999.
23. Haennel R. Effects of hydraulic circuit training on cardiovascular function. *Med Sci Sp Ex*: 21(5): p. 605, 1989.
24. Hamilton RJ, Paton CD, and Hopkins WG. Effect of High-Intensity Resistance Training on Performance of Competitive Distance Runners. *Int J of Sp Physiol Per*: 1(1): p. 40-49, 2006.
25. Hickson RC, Rosenkoetter MA, Brown MM. Strength training effects on aerobic power and short-term endurance. *Med Sci Sp Ex*: 12(5): 336-339, 1980.
26. Hoff JJ. Maximal strength training improves aerobic endurance performance. *Sc J Med Sci Sp*: 12(5): p. 288-295, 2002.
27. Hunter GR et al. Tendon length and joint flexibility are related to running economy. *Med Sci Sp Ex*: 43(8): p.1492-1499, 2011.
28. Hurley BF. Effects of Strength Training on Muscle Hypertrophy and Muscle Cell Disruption in Older Men. *Int J of Sp Med*: 16(06) p. 378-384, 1995.
29. Johnston RE et al. Strength training female distance runners: impact on running economy. *J Str Con*: 11(4): p. 224-229, 1997.
30. Jung AP. The impact of resistance training on distance running performance. *J Sp Med*: 33(7): p. 539-552, 2003.
31. Kaikkonen HH. The effect of heart rate controlled low resistance circuit weight training and endurance training on maximal aerobic power in sedentary adults. *Sc J Med Sci Sp*: 10(4): p. 211-215, 2000.
32. Kawakami Y, Abe T, Kuno SY, and Fukunaga T. Training-induced changes in muscle architecture and specific tension. *Eur J Appl Physiol Occup Physiol*: 72(1-2): p.37-43, 1995.
33. Kelly CM, Burnett AF, and Newton MJ. The Effect of Strength Training on Three-Kilometer Performance in Recreational Women Endurance Runners. *J Str Con*: 22(2): p. 396-403, 2008.
34. Kraemer WJ, Deschenes MR, Fleck SJ. Physiological adaptations to resistance exercise. Implications for athletic conditioning. *Sp Med*: 6(4): p.246-56, 1988.
35. Kraemer WJ et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol*: 78(3): p.976-989, 1995.
36. Lake M, Cavanaugh P. Six weeks of training does not change running mechanics or improve running economy. *Med Sci Sp Ex*: 28: p.860-869, 1996.
37. Lemura LM et al. Lipid and lipoprotein profiles, cardiovascular fitness, body composition, and diet during and after resistance, aerobic and combination training in young women. *Eur J Appl Physiol*: 82: p.451-458, 2000.

38. Luden ND et al. Skeletal muscle plasticity with marathon training in novice runners. *Scand J Med Sci Sp*: doi: 10.1111/j.1600-0838.2011.01305.x, 2011.
39. Lieber R. *Skeletal Muscle Structure and Function*. 1992.
40. Marcinik EJ. Effects of strength training on lactate threshold and endurance performance. *Med Sci Sp Ex*: 23(6): p. 739, 1991.
41. McCarthy JP. Compatibility of adaptive responses with combining strength and endurance training. *Med Sci Sp Ex*: 27(3): p. 429, 1995.
42. Mikkola J et al., Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in Young Distance Runners. *Int J Sp Med*: 28(7): p. 602-611, 2007.
43. Millet GP et al. Effects of concurrent endurance and strength training on running economy and VO₂ kinetics. *Med Sci Sp Ex*: 34(8): p. 1351-1359, 2002.
44. Narici M. Human skeletal muscle architecture studied in vivo by non-invasive imaging techniques: functional significance and applications. *J Electromyogr Kinesiol*: 9(2): p97-103, 1999.
45. O'Hara R et al. Leg resistance training: effects upon VO_{2peak} and skeletal muscle myoplasticity. *J Ex Physiol*: 7(5): p. 27, 2004.
46. Paavolainen L., Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol*: 86(5): p. 1527, 1999.
47. The 2009 National Runners Survey. *Running USA*. 2009.
48. Saltin B, Astrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol*: 23: p.353-358, 1967.
49. Saltin B et al. Physical Training in Sedentary Middle-aged and Older Men II. Oxygen Uptake, Heart Rate, and Blood Lactate Concentration at Submaximal and Maximal Exercise. *Sc J Clin Lab Inv*: 24(4): p.323-324, 1962.
50. Saunders PU et al. Short-Term Plyometric Training Improves Running Economy in Highly Trained Middle and Long Distance Runners. *J Str Con*: 20(4): p.947, 2006.
51. Scrimgeour AG et al. The influence of weekly training distance on fractional utilization of maximum aerobic capacity in marathon and ultramarathon runners. *Eur J Appl Physiol Occ Physiol*: 55(2): p.202-209, 1986.
52. Seynnes OR, M. de Boer, and Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol*: 102(1): p.368-73, 2007.
53. Sjodin B, Jacobs I, Svendsen J. Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA. *J Appl Physiol*: 49(1): p.45-57, 1982.
54. Spina RJ. Cardiovascular adaptations to endurance exercise training in older men and women. *Ex Sp Sci Rev*: 27: p.317-32, 1999.
55. Spina RJ, Ogawa T, Martin WH, et al. Exercise training prevents decline in stroke volume during exercise in young healthy subjects. *J Appl Physiol*: 72: p.2458-62, 1992.
56. Starkey DB, Pollock ML, Ishida Y, Welsch MA, Brechue WF, Graves JE, and Feigenbaum MS. Effect of resistance training volume on strength and muscle thickness. *Med Sci Sp Ex*: 28(10): p.1311-20, 1996.

57. Taipale RS et al. Strength training in endurance runners. *Int J Sp Med*: 31(7): p. 468-476, 2010.
58. Trappe S et al. Single fiber muscle adaptations with marathon training. *J Appl Physiol*: 101: p.721-727, 2006.
59. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Str Con*: 17(1): p.60-67, 2003.
60. Wenger HA, Bell GJ. The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. *Sp Med*: 3: p.346-56, 1986.
61. Wilmore JH, Royce J., Girandola RN, Katch FI, and Katch VI. Physiological alterations resulting from a 10-week program of jogging. *Med Sci Sp Ex*: 2(1): p. 7-14, 1970.
62. Wilmore JH, Parr RB, Girandola RN, et al. Physiological alterations consequent to circuit weight training. *Med Sci Sp Ex*: 10(2): p.79-84, 1978.