# The Effects of Aerobic Exercise on Strength Performance Under Varying Durations of Recovery

by

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B.Sc., Kinesiology (Hon)
University of Victoria, 1998

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

in the School of Physical Education

We accept this thesis as conforming
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## ABSTRACT

The purpose of this study was to determine if the type and intensity of aerobic training affects the amount of work that can be performed in a subsequent strength training session after recovery periods of 4, 8, and 24 hours. Sixteen male subjects actively involved in sports (hockey, rowing, soccer, basketball, rugby) participated in the study and were divided into two groups, MAX (8) and SUB (8). Aerobic training consisted of either six, 3-minute intervals at 85-100% power output at cycle $\dot{V}O_2$ max (POCMAP) separated by 3-minute recovery intervals (MAX) or 36 minutes of continuous aerobic training at approximately 70% POCMAP (SUB). Each participant performed 4 sets of both bench press and leg press at approximately 75% 1RM on 4 different occasions. Three occasions were preceded by aerobic training with recovery periods of 4, 8, or 24 hours, while the fourth was used as a control. Total repetitions in leg press were affected by length of recovery following aerobic training while total repetitions in bench press were unaffected. Both the 4 and 8-hour recovery conditions resulted in significantly fewer total leg press repetitions than both the control and 24-hour recovery conditions. There was no difference between both the control and 24-hour conditions. No main effect was shown with respect to the type of aerobic training. It was concluded that regardless of the type, when aerobic training precedes strength training, the volume of work that can be performed is diminished for up to 8 hours. This impairment appears to be localized to the muscle groups involved in the aerobic training.

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## Acknowledgements

I would like to express my thanks to my supervisor, Dr. Howie Wenger, for all his insights and guidance, both with this degree and in my life. Thank you Howie for your enthusiasm, words of encouragement, and your positive attitude. I have learnt far more than the "process" that I set out to learn in the beginning and I have fond memories of the past two years. Burning chicken, sushi feasts, and furry friends are a few things that come to mind. It has been an enjoyable journey and adventure and I look forward to more in the future with you.

Many thanks to all my committee members Dr. Dave Docherty, Dr. John Anderson, and Dr. Lynneth Wolski for their insights and comments regarding my study. Special thanks to Dave Docherty for the countless hours of discussion and interest in examining the "interference effect" over the past 4 years.

There are four people I would like to thank for all their help with my collection of data. Kelly, Carrie, Tammy, and Sam - thanks! You all were great and seemed to have no problems putting up with my crazy scheduling. Special thanks to all my participants who endured the training and testing and still are able to say hi to me. Without them this study would not have been possible. Many thanks to Stef, Sean, Jeff, Kirstin, Holly, Dona ,and Jason, who all offered their brain to be picked when needed as good friends would.

I would also like to thank my family. Their support and love has made it possible to achieve my goals and continue to learn. Finally a special thank-you to my best friend Trina whose words of encouragement and love make life easier and more enjoyable. Thank you for always showing interest in both my thoughts and my work.

## Dedication

I would like to dedicate this thesis to my mother, Mary Sporer, who deserves to have her name in print. You have always been supportive of my dreams and taught me to believe in myself and the value of both respect and hard work. Thank-you.

## Introduction

Many sports require athletes to possess high levels of both muscular strength and aerobic fitness in order to be competitive. Athletes may train for both fitness components during the same training phase (hereafter referred to as concurrent training). Concurrent training results in impaired strength improvements when compared to strength training alone (Dudley & Djamil, 1985; Hunter et al., 1987; Hickson, 1980; Hennessy & Watson, 1994). However, strength improvements have also been shown not to be affected by concurrent training (Abernethy & Quigley, 1993; McCarthy, Agre, & Graf, 1995; Sale, MacDougall, Jacobs, & Garner, 1990) and one study has shown inhibition of aerobic power development (Nelson, Arnall, Loy, Silvester, & Conlee, 1990). The effects of training for both fitness components concurrently are not clear although it is accepted that concurrent training results in impaired strength gains (Leveritt, Abernethy, Barry, & Logan, 1999; Chromiak & Mulvaney, 1990).

Dudley and Djamil (1985) demonstrated that concurrent high velocity strength and aerobic power training resulted in smaller strength gains than strength training alone, while gains in $\dot{V}O_2$ max were unimpaired. These findings are in agreement with those of Hickson (1980) who found that prolonged concurrent training (> 7 weeks) resulted in decreased strength gains without compromising improvements in aerobic power. Sale and colleagues (1990) also showed that same day concurrent training resulted in impaired improvements in strength when compared to training for strength and aerobic power on alternate days. Hennessy and Watson (1994) showed that interference appears to be specific to the muscle groups used in both aerobic and strength training. Only lower body strength gains were impaired when running was the method of aerobic training.

Gains in upper body strength were unaffected by concurrent training in this manner. The physiological causes of these compromised strength gains are not well understood. However, several hypotheses have been proposed based on research evidence of the physiological requirements of, and adaptations to strength or endurance training when performed exclusively.

It is suggested that impaired strength gains may be due to increased fatigue of the muscle (Leveritt *et al.*, 1999; Craig *et al.*, 1991; Sale *et al.*, 1990). This fatigue hypothesis (Leveritt *et al.*, 1999; Craig *et al.*, 1991) states that under concurrent training conditions, the amount of work that can be performed in each strength training session is reduced due to fatigue from prior aerobic training (Leveritt *et al.*, 1999). Both the sequence of training and the amount of recovery between training sessions affect fatigue state and therefore may provide support for the fatigue hypothesis (Leveritt *et al.*, 1999). Compromised strength gains are more pronounced when aerobic training precedes strength training (Bell, Petersen, Quinney, & Wenger, 1988). Furthermore, several studies have shown that prior aerobic training limits the amount of work that can be performed in subsequent strength training session (Abernethy, 1993; Leveritt & Abernethy, 1999; Sale *et al.*, 1990). Abernethy (1993) showed impaired isokinetic strength performance at a variety of speeds, when both long slow duration (LSD) and interval (INT) aerobic exercise were performed 4 hours prior. The effect was similar for both LSD and INT. They concluded that although decreased performance in isokinetic strength occurred, it is not possible to determine whether or not this will result in compromised strength over the course of a training program. Leveritt and Abernethy (1999) have provided further support for the acute effects of aerobic exercise on subsequent strength performance. High intensity interval training impaired both isokinetic and isoinertial strength (squat) 30 minutes post aerobic exercise and isoinertial strength was more affected than isokinetic strength. As well, the number of repetitions performed in all sets of the subsequent squat exercise was significantly reduced. Strength training programs often utilize isoinertial exercises (squat, leg press, and bench press) as opposed to isokinetic training devices, as well as two to four exercises per muscle group. Therefore, it is possible that a greater impairment may occur in the latter exercises of a training session and a decreased ability to perform work may lead to compromised strength gains over the duration of a training program. Thus it seems that both sub-maximal and maximal aerobic training, when performed prior, compromise strength performance in a subsequent strength training session.

Only one training study specifically compared concurrently trained groups with different periods of recovery between strength and aerobic training sessions. Sale and colleagues (1990) changed the sequence of training between strength and aerobic training on the same day and alternate days. Although training programs were the same, the group training on alternate days showed significantly greater improvements in maximal leg press strength than those training on the same day at both 10 and 20 weeks (18% and 25% versus 7% and 11%). Furthermore, average training volume for each strength training session was significantly lower for the same day training group even though the sequence of aerobic and strength training alternated each session. The authors concluded that concurrently training both strength and aerobic fitness on the same day impaired strength gains and that this was possibly due to a decrease in average volume per strength training session. No control group was used to verify if strength gains were compromised in the group training on alternating days. However, it appears that 24 hours of recovery following aerobic training results in improved ability of the muscle to perform work as compared to 30 minutes (Sale *et al.*, 1990). Abernethy (1993) suggested that this impairment lasts at least 4 hours. As yet, a time frame for the optimum recovery period for subsequent strength training has not been determined.

It has been shown that concurrent strength and aerobic training results in compromised strength gains (Hickson, 1980; Dudley & Djamil, 1985; Sale *et al.*, 1990, Hennessy & Watson, 1994). Compromised strength gains appear to be more pronounced when strength training follows aerobic training (Bell *et al.*, 1988) and this may be due to a decreased ability of the muscle to perform work in a subsequent strength training session (Abernethy, 1993; Leveritt & Abernethy, 1999; Sale *et al.*, 1990). The optimum time required between an aerobic and strength training session to ensure adequate recovery of the working muscles has not yet been determined. Therefore, the purpose of this study is to examine the effects of two different types of aerobic training on subsequent strength training performance under varying durations of recovery and to determine if there is a muscle specific effect.

## Statement of the Problem

Aerobic exercise prior to a strength training session results in impairment to the amount of work that can be performed (Abernethy, 1993; Leveritt and Abernethy, 1999; Sale et al., 1990). The effect of different recovery times between aerobic training and strength training has not yet been investigated. Therefore the major purposes of this study are:

1. To compare the effects of aerobic training on subsequent strength training after recovery periods of 4, 8, and 24 hours.
2. To determine if the type and intensity of aerobic training differentially effects the amount of work that can be performed in a subsequent strength training session after recovery periods of 4, 8, and 24 hours on different muscle groups.

## Research Questions

1. Does the length of the recovery period affect the amount of work that can be performed in a strength training session following an aerobic training session?

2. Is the amount of work that can be performed for a specific length of a recovery period affected by both the type and intensity of prior aerobic training?

3. If impairment in ability to perform work occurs, is it specific to the muscle groups used in the prior aerobic training?

## Hypotheses

The following null hypothesis will be tested:

$H_{o1}$: High intensity aerobic intervals at 85-100% $\dot{V}O_2$ max power output (PO) will have no significant effect on the volume of work performed over 4 sets of both bench press and leg press at approximately 75% 1RM when performed either 4, 8, or 24 hours later.

$H_{o2}$: Sub-maximal aerobic training at approximately 70% $\dot{V}O_2$ max PO will have no significant effect on the volume of work performed over 4 sets of both bench press and leg press at approximately 75% 1RM when performed either 4, 8, or 24 hours later.

$H_{o3}$: There will be no significant difference between the effects of sub-maximal aerobic training at approximately 70% $\dot{V}O_2$ max PO, and high intensity aerobic intervals at 90-100% $\dot{V}O_2$ max PO, on the total work over 4 sets of both bench press and leg press at approximately 75% 1RM with recovery periods of 4, 8, and 24 hours.

## Operational Definitions

1. **1 Repetition Maximum (1RM):** the maximal amount of weight that can be lifted for 1 repetition only.
2. **Sub-maximal Aerobic Training:** training that has a primary goal of increasing aerobic capacity using a training intensity of approximately 70% power output at peak cycle ergometer $\dot{V}O_2$ max (POCMAP).
3. **High Intensity Aerobic Training:** training that has a primary goal of increasing aerobic power using a training intensity of 85-100% POCMAP
4. **Strength Training:** isoinertial resistance training that has a primary goal of increasing 1RM strength using 4 sets to failure at approximately 75% 1RM.
5. **Concurrent Training:** Training that includes both strength and either sub-maximal or high intensity aerobic interval training within 48 hours of each other.
6. **Interference:** impaired strength gains when both strength and aerobic power are trained concurrently.
7. **Trained Subject:** An individual who has been involved in both strength and high intensity aerobic training for a period of at least 6 months in the last 2 years and is currently training.
8. **Strength Training Volume:** the total number of repetitions over 4 sets at a relative load of approximately 75% 1RM.

## Assumptions

1. The load at which the subjects were required to train at was sufficient to cause an improvement in $\dot{V}O_2$ max over an extended training period.
2. Subjects went to failure in each set on every day of testing.
3. Bikes were calibrated equally and that power output for all aerobic training sessions was consistent.
4. Subjects made a consistent effort in all strength testing sessions.
5. Participants obeyed the training and activity guidelines set out for the study.

## Delimitations/Limitations

1. 16 subjects were used.
2. Only college-aged males participated in this study.
3. The subjects were from various sporting backgrounds.
4. Volume of work was a non-invasive measurement of muscular fatigue and therefore the physiological source of fatigue was unavailable.
5. The leg press and bench press are multi-joint exercises and therefore this limited the ability to identify specific muscle groups experiencing muscular fatigue.
6. The leg press and bench press were only monitored during this study and this limits the ability to generalize the results to other strength training exercises.
7. The load was approximately 75% of the 1RM of each subject and this limits the ability to generalize the results to other training intensities.
8. It was up to the participants to go to failure in each set for each strength training exercise under each condition.

9. Only the cycle ergometer was used to perform aerobic exercise and this limits the ability to generalize the results to other forms of aerobic activity.
10. Muscle fiber composition may vary across individuals and therefore the amount of fatigue experienced prior to strength training may have varied.
11. Cycle training loads were applied by hand and this may have resulted in loading error.
12. Participants in the maximal interval group were unable to complete all intervals at 100% $\dot{V}O_2$ max power output (POCMAP) and therefore had to use lower intensities (> 85% POCMAP).

# Methods

## Participants

Following approval by the University of Victoria Human Research Ethics Committee, 17 male participants were recruited from the university athletic community. All were actively involved in sports (hockey, rowing, soccer, basketball, rugby) and were therefore accustomed to training at maximal intensities. In addition, all participants were currently strength training at the time of the study and had strength trained for a period of at least six consecutive months in the 2 years prior. Previous experience performing high intensity aerobic intervals was also required. All testing and training procedures were thoroughly explained and participants were informed of any potential risks and the training intensities to be used. All participants medically screened with a Par-Q, signed informed consent, and confidentiality of results was assured.

One participant withdrew prior to completing the study due to an injury and therefore only 16 subjects completed all training and testing conditions. One participant performed a dumbbell press instead of the bench press due to a previous shoulder injury.

## Design

The study followed a randomized within participants design. Participants were randomly divided into one of two groups, a high intensity aerobic interval training group (MAX) or a sub-maximal aerobic continuous training group (SUB). Participants were then required to attend on 9 different occasions. One session required participants to perform an initial 1 RM leg press and bench press test to determine loads to be used in strength training sessions. A second session was used to determine the cycle $\dot{V}O_2$ max of each participant and power output at $\dot{V}O_2$ max (POCMAP). The remainder of the training and testing sessions (3 aerobic training sessions and 4 strength testing sessions) were randomized with a minimum of 72 hours rest between each strength testing session. All strength testing sessions were performed during a 3-hour window in the evening to account for diurnal effects. See Appendix E for diagram of design layout

All subjects were requested to comply with the following training guidelines while participating in the study:

1.) No strength training for a minimum of 48 hours prior to a strength testing session
2.) No aerobic training within 24 hours prior to an aerobic training session and under the control condition, no aerobic training 48 hours prior to the strength testing session
3.) Activity on days prior to both training and testing be kept to a minimum

Due to all participants being active in other sports, training and testing sessions were arranged around team training schedules. Five Monarch cycle ergometers were calibrated prior to, during, and at the end of the study to ensure accuracy and consistency of the training intensities. All participants performed strength testing sessions on the same incline leg press (Bodymasters) and bench press. At least one Professional Fitness and Lifestyle Consultant was present at all training and testing sessions and all other assistants were trained and experienced in all testing procedures.

**$VO_2$max Test.** Mass (kg) and height (cm) was obtained prior to the $\dot{V}O_2$ max test being performed. Participants were instructed to do their own stretching before the cycling test began. The test itself was an incremental test and each participant began with one two-minute stage at 1.0 kp. Each stage thereafter lasted one minute and resistance was increased by 0.5 kp for each stage until the participant could no longer continue. It was requested that pedal revolutions (RPM) be maintained between 70 and 80 RPM. Oxygen consumption was measured using a Sensormedics Vmax System and was expressed relative to body mass. $\dot{V}O_2$ max was considered to have been achieved when 2 or more of the following criteria had occurred: (a) there was a plateau ($<2$ ml•kg$^{-1}$•min$^{-1}$ increase) or decrease in oxygen consumption with a subsequent increase in workload; (b) age predicted max heart rate had been achieved; (c) a respiratory quotient of 1.1 or greater had been achieved; (d) the participant reached fatigue. RPM were recorded at the end of each stage and, combined with resistance, was used to determine POCMAP in watts. Maximum heart rate (HRMAX) was monitored and recorded using a Polar Sport heart rate monitor and was then used to monitor the intensity of the aerobic training sessions.

**MAX Aerobic Training.** Participants in group MAX performed interval training consisting of a five minute warm-up, six 3-minute work intervals separated by three minute recovery periods, and a five minute cool-down. During warm-up, cool-down, and recovery periods, training intensity was at approximately 40% POCMAP. The first work interval was performed at approximately 95-100% POCMAP for the entire three minutes while subsequent intervals were adjusted to both ensure participant was training at HRMAX and was able to complete the training session. None of the intervals, however, were reduced below approximately 85% of the load achieved at POCMAP and the same loading protocol was used for the next two aerobic training sessions to ensure consistency. RPM were recorded at the 1st, 2nd,and 3rd minute of each work interval and were used to calculated average watts and work performed during each work interval. These were in turn used to calculate the average watts and work (kcal) performed during each training session. Average RPM were also recorded during each three-minute recovery period.

**SUB Aerobic Training.** Participants in group SUB performed submaximal aerobic training consisting of a five minute warm-up, 36 minutes at approximately 70% POCMAP, and a five minute cool-down. RPM were recorded at 6 min intervals of the submaximal training portion. Average watts and work (kcal) per training session were calculated to ensure consistency.

**1RM Strength Testing.** Participants were required to perform a general warm-up consisting of 5 min of cycling and stretches of their choice. All leg press testing was performed on a BodyMasters incline leg press of approximately 45 degrees while bench press was performed on a standard bench press using a 45lb Olympic style bar. Leg press testing preceded bench press testing and both followed the same protocol. Participants were required to perform between six and eight repetitions of approximately 50% their 1RM followed by 4 min rest, and then perform between 2 and 4 repetitions of approximately 75% their 1RM. From this point forward a 4 min rest was allotted between subsequent attempts at a 1RM. If the participant was able to complete one repetition, the weight was increased and another attempt would be made. If the participant was unable to complete the repetition, the weight from the last successful attempt was recorded as the 1RM. The 1RM leg press was performed as a concentric contraction from a joint angle of 90° at the knee. At the end of the testing session, participants were requested to hold the empty sled at a 90° angle at the knee. A piece of tape, approximately 3.75 cm wide, was used as a spotting device for the strength testing sessions to ensure an angle of 90° was obtained each rep (90° marker). This was then measured from a fixed point on the leg press to ensure consistency across testing sessions. For the bench press, participants were required to lower the weight controlled to within 2.5 cm of their chest and raise the weight to full extension of the arms. Placement of the hands was at the discretion of the participant, however, the distance between the hands was measured and this was required to be constant in all bench press testing sessions.

**Strength Testing.** Upon arrival to the training facility, participants were asked to report their Readiness to Work (Appendix C). Strength testing was designed to mimic a typical resistance training session. Participants were required to performed 4 sets of leg press followed by 4 sets of bench press at a load of approximately 75% 1RM. Each set was separated by a recovery period of 3 minutes with all sets of leg press being performed prior to the bench press. A break of approximately 5 minutes occurred between bench press and leg press exercises. Warm-up consisted of cycling for approximately 5 minutes followed by general stretching. One warm-up set was performed for both the leg and bench press and was with a load self-selected by the participant. This load was between 50 and 70% of the training load and no more than 8 repetitions were allowed. To ensure consistency, the warm-up sets for both exercises were the same in all conditions. A complete repetition for the leg press consisted of lowering the weight to the 90° marker and raising the weight back to its original position. Verbal confirmation was given when the 90° marker had been reached and participants were encouraged to wait until confirmation was received prior to raising the weight. A complete repetition for the bench press consisted of lowering the weight in a controlled manner to within 2.5 cm of the chest and raising the weight to full extension of the arms. Only complete repetitions were counted. Repetitions that did not meet the criteria were not counted. An assistant who was both trained and experienced in the testing protocol administered all strength tests. The assistant was also blind to the condition each participant was under in order to eliminate any pre-conceptions of each participants' ability to perform work. Total reps were counted for each set and session, and volume per session was calculated by multiplying total repetitions with load.

## Data Analysis

A repeated measures analysis of variance was conducted for each of the dependent variables of leg press (LP) and bench press (BP) using the mean of total repetitions per training session (MTRL and MTRB respectively) under each condition. Standard error was reported as interest was in how groups responded to the treatment. Paired sample t-tests were conducted for post hoc tests for which a main effect was shown. An alpha level of 0.05 was used for all statistical tests.

# Results

## Participant Characteristics

The 16 male participants included 2 rugby players, 3 hockey players, 1 rower, 2 tennis players, a soccer player, and 7 recreational athletes. Both Table 1 and Table 2 summarize the pre-test values and characteristics of all participants in the high intensity, interval aerobic training group (MAX) and the submaximal, continuous aerobic training group (SUB). No significant differences were found between each group on any of the measures.

Table 1

Mean, Range, and Standard Error (SE) for Age, and Height of MAX (N=8) and SUB (N=8) groups.

| | | Age (yrs.) | Height (cm) | Weight (kg) |
|---|---|---|---|---|
| MAX | Mean | 25 | 179.4 | 83.0 |
| | Range | 19-29 | 171.5-189 | 70.4-91.0 |
| | SE | 1 | 1.8 | 2.1 |
| SUB | Mean | 26 | 179.4 | 82.0 |
| | Range | 20-32 | 173-191 | 73.0-97.5 |
| | SE | 1 | 2.5 | 2.8 |

Table 2

Mean, Range, and Standard Error (SE) for $VO_2$max, Power Output at $VO_2$max (POCMAP), Max Leg Press (MLP), and Max Bench Press (MBP) of MAX (N=8) and SUB (N=8) groups.

| | | $VO_2$max ($mL \cdot kg^{-1} \cdot min^{-1}$) | POCMAP (watts) | MLP (lbs) | MBP (lbs) |
|---|---|---|---|---|---|
| | Mean | 55.8 | 382 | 864 | 231 |
| MAX | Range | 45.9-62.7 | 311-451 | 585-1140 | 180-335 |
| | SE | 1.8 | 16 | 68 | 17 |
| | Mean | 57.5 | 384 | 783 | 219 |
| SUB | Range | 44.4 - 75.8 | 312-468 | 655-1080 | 165-305 |
| | SE | 3.2 | 18 | 52 | 15 |

## Aerobic Training

Mean power output per aerobic training session (MPO), and mean session training work (TW) were significantly different between the two groups (Table 3). Group MAX worked at a significantly higher wattage (314 vs. 248, $p=0.002$) while performing significantly less training work (TW) over the 36 minutes (81 kcal vs. 128 kcal, $p<0.001$). Difference in work between groups when recovery intervals were included (TWIR) was not statistically significant (116 kcal vs. 128 kcal, $p=0.151$).

Table 3

Mean Power Output (MPO), Mean Training Work (TW), Mean Training Work Including Recovery (TWIR), and Standard Error (SE) in Each Aerobic Training Session for Both MAX and SUB.

| | MPO (Watts) | TW (kcal) | TWIR (kcal) |
|---|---|---|---|
| MAX | 314[a] | 81[b] | 116 |
| SE | 11 | 3 | 4 |
| SUB | 248[a] | 128[b] | 128 |
| SE | 13 | 7 | 7 |

Corresponding letters denote significant differences between conditions ($p<0.05$).

**Leg Press**

Mean total repetitions over 4 sets of leg press (MTRL) was significantly affected by the amount of recovery time between aerobic and strength training sessions

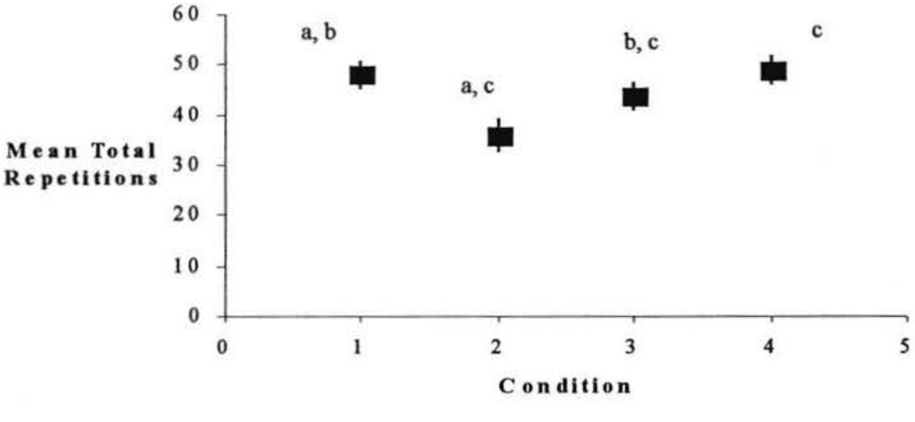

Figure 1. Comparison of mean total repetitions of leg press per recovery condition ($n=16$). Corresponding letters denote significant differences between conditions ($p<0.05$).

(F=17.217, p=0.000). Type of aerobic training (MAX, SUB) showed no main effect on MTRL (F=0.147, p=0.707) nor was there any interaction between type of training and recovery condition (F= 0.087, p=0.967). At both 4 and 8 hours, repetitions were significantly lower (12 repetitions, 25%, $p<0.001$; and 4 repetitions, 9% p=0.005 respectively) when compared to the control (Figure 1, Table 4). MTRL was significantly higher when recovery time was increased from 4 to 8 hours (7 repetitions, 22%, p=0.002) and from 8 to 24 hours (5 repetitions, 12%, p=0.009). There was no difference in MTRL between the control and 24 hour recovery conditions (48 vs. 49, p=0.617). The general trend was that as recovery time from aerobic exercise increased up to 24 hours, so did MTRL.

Table 4

Mean Volume in Total Reps Over 4 Sets and Standard Error (SE) for Leg Press (MTRL) for All Participants (COMB).

| | MTRL (reps) | | | |
|---|---|---|---|---|
| | Control | 4-hour | 8-hour | 24-hour |
| COMB (n=16) | 48 | $36^{a,c}$ | $44^{a,b,c}$ | 49 |
| SE | 3 | 3 | 3 | 3 |

[a] = Significantly different from control $p<0.05$; [b] = Significantly different from 4-hour $p<0.05$; [c] = Significantly different from 24-hour $p<0.05$

## **Bench Press**

Mean total repetitions over 4 sets of bench press (MTRB) was not affected by either the amount of recovery time from aerobic training or type of aerobic training (F=0.076, p=0.972 and F=0.492, p=0.694 respectively). Mean repetitions per condition are shown for all subjects in Table 5.

Table 5

Mean Volume in Total Reps Over 4 Sets and Standard Error (SE) Bench Press (MTRB) for All Participants (COMB).

| | MTRB (reps) | | | |
|---|---|---|---|---|
| | Control | 4-hour | 8-hour | 24-hour |
| COMB (n=16) | 32 | 32 | 32 | 32 |
| SE | 1 | 1 | 1 | 1 |

## Discussion

This study demonstrated that when strength training follows aerobic training, the volume of work (total repetitions over 4 sets at approximately 75% 1RM) that can be performed in a strength training session is diminished. The extent to which volume is compromised appears to be both dependent on the length of the recovery period between training sessions and limited to the muscle groups utilized in aerobic training. Although it can be assumed that this is due to an increased level of muscular fatigue, without additional measures such as muscle biopsies and electromyography readings, it is difficult to interpret the cause of such fatigue (hydrogen ion, energy supply, neural fatigue, or structural damage).

The fatigue hypothesis states that under concurrent training conditions, the amount of work that can be performed in each strength training session is reduced due to fatigue from prior aerobic training thereby resulting in impaired strength gains (Leveritt *et al.*, 1999; Craig *et al.*, 1991). Understanding that total work is an important factor in optimizing the strength training response (Fleck & Kraemer, 1997), a reduction in work may be responsible for the compromised improvements in strength seen in concurrent training studies (Dudley & Djamil, 1985; Hunter *et al.*, 1987; Hickson, 1980; Hennessy & Watson, 1994).

The major finding in this study is that the volume of work that can be performed in previously aerobically trained muscles is dependent on the length of recovery between aerobic and strength training sessions. Aerobic cycling resulted in decreased volume of work performed in the leg press exercise (MTRL) with both 4 and 8 hours of recovery between sessions (25% and 9% respectively). When 24 hours of recovery was allotted, MTRL was equal to that of the control condition. A general trend was seen that as recovery time increased, MTRL also increased significantly (Figure 1).

Some of these results were expected. Leveritt and Abernethy (1999) showed that isokinetic and isoinertial strength were both impaired 30 minutes after high intensity aerobic interval exercise (5 minutes @ 60-100% $\dot{V}O_2$ max). Isoinertial strength appeared to be affected to a greater extent than isokinetic strength. A 27% drop in total repetitions over 3 sets @ 80% 1RM of the back squat was observed. As well, Abernethy (1993) demonstrated that isokinetic strength was impaired for up to 4 hours following high intensity aerobic interval training similar to Leveritt and Abernethy (1999). If isoinertial strength is affected by prior aerobic training to a greater extent than is isokinetic strength (Leveritt & Abernethy, 1999), it could be assumed that isoinertial strength would be impaired for up to 4 hours as well. The current findings support this notion and further suggest that compromises in strength may last up to 8 hours post-aerobic training.

Only one study examined the effect of prior aerobic activity on subsequent strength performances with recovery periods greater than 4 hours. Sherman and colleagues (1984) showed that marathon participants experienced decreases in maximal peak torque for up to 7 days. Although the present findings show a decrease in MTRL with only 8 hours of recovery, the results of Sherman and colleagues (1984) would suggest that the decrement would be greater than 4 reps. Furthermore, the current study suggests that strength is restored within 24 hours of prior aerobic training. Differences may be due to the duration and nature of the aerobic training. Sherman and colleagues (1984) tested strength measures following completion of a marathon. Time to completion would be much longer than the length of aerobic training in the present study and would likely result in greater fatigue. In addition, running is associated with more eccentric loading than is cycling and therefore muscle damage may have resulted in greater strength impairments.

Both Keizer and colleagues (1987) and Kroon and Naeije (1988) have also shown that approximately 24 hours is not enough time to recover from muscular fatigue. However different evaluation and training methods make comparison to the current study inappropriate. Keizer and colleagues (1987) evaluated performance following recovery using a graded cycle test while Kroon and Naeije (1988), although evaluating maximal strength and endurance time, utilized resistance training as their exhaustive exercise rather than aerobic training.

It is also possible that the number of sets used in the current study may have hidden any fatigue that may still have been present at 24 hours. Multiple sets of multiple exercises are generally used when training for strength of a specific muscle group. Had a second exercise or more sets been used, a lower MTRL may have been seen at 24 hours when compared to the control.

The current findings suggest that if 24 hours of recovery are allotted between aerobic and strength training, no loss in strength training volume will be experienced. This is in agreement with Sale and colleagues (1990) who demonstrated that same day concurrent training resulted in significantly less volume of work per strength training session when compared to alternate day training. Sale and colleagues utilized similar strength (15-20RM) and aerobic (90-100% $\dot{V}O_2$ max intervals) training protocols as the current study. Alternate day training also resulted in significantly greater improvements in strength than same day training over 20 weeks. It was hypothesized that compromised gains may be reflective of the compromised volume of work per strength training session that was experienced with same day training. Although Sale and colleagues (1990) did not use a control group to determine whether or not 24 hours was sufficient time for complete recovery, these findings are in agreement with the current finding that longer recovery periods allow for a greater volume of work to be performed.

The length of recovery periods in other concurrent training studies either vary or are unclear making it difficult to show relationships to the present findings and those of Sale and colleagues (1990). However, conclusions linking decreased volume of work in a single session to compromised strength improvements over a training study should be made with caution. Fatigue, as well, has been shown to be an important factor contributing to the strength-training stimulus (Rooney, Herbert, & Balnave, 1994). If the muscle is taken to fatigue at a certain load in each set, it is possible that the training effect has occurred regardless of the number of repetitions. Further research is necessary to determine the extent to which fatigue and volume contribute to the strength stimulus.

The stronger, more powerful fast twitch (FT) muscle fibers are primarily responsible for producing the force required when strength training. Although aerobic training primarily recruits slow twitch (ST) fibers, as intensity of training increases, FT muscle fibers are taxed to a greater extent (Dudley, Abraham, & Terjung, 1982). It would be expected then, that higher intensity aerobic training would result in a greater amount of fatigue prior to strength training. Although no effect of type of aerobic training was shown on MTRL in the current study, the findings support this notion. The nature of the training design did not allow for equal amounts of training work between groups. SUB performed continuous training while MAX performed interval training.

Due to recovery intervals in MAX being at a load that could not be considered to be training the aerobic system (~40% POCMAP), mean training work (MTW – not including the recovery intervals) over the 36 minutes is significantly less than that performed in SUB (81 kcal vs. 128 kcal, respectively). Even with a lower MTW, MAX showed similar decrements in MTRL with both 4 and 8 hours of recovery as did SUB. This suggests that the fatigue experienced per unit of work in the MAX protocol is greater and possibly longer lasting than that experienced in the SUB protocol. Had more sets been performed or the duration of aerobic training been different, an effect by the type of training may have been seen.

Abernethy (1993) demonstrated a similar response using slightly different training and testing protocols. Using slow continuous cycling (150 min @ ~35% $\dot{V}O_2$ max) and interval training (5 repetitions of 5 minutes @ 60 to 100% $\dot{V}O_2$ max), Abernethy showed that isokinetic strength was similarly affected at a variety of speeds by both training conditions. Unfortunately, no calculation of total work performed during aerobic training performed by each group was reported.

A third major finding in this study is that strength impairments appear to be limited to the muscle groups used in prior aerobic training. There was no difference in MTRB when length of recovery period was changed. If fatigue from prior aerobic training occurred, it would be expected that it be located within the muscle groups used in aerobic training. The mechanisms of muscular fatigue are specific to the muscle groups utilized and would not be expected in the muscles of the upper body when aerobic training was primarily performed with the lower body. Unfortunately there appears to be no research examining the acute effects of aerobic training on the strength of nonaerobically exercised muscle groups. Some training studies have examined the effects of concurrent training on upper body strength using lower body muscle groups for aerobic training (Hennessy & Watson, 1994; Kraemer *et al.*, 1995). Both Hennessy and Watson (1994) and Kraemer and colleagues (1995) demonstrated that over the course of a training study, improvements in upper body strength were not affected by concurrent training. It is possible that concurrently trained groups in both of these training studies were able to maintain similar volumes of upper body training as strength only trained groups. However this conclusion is made with caution as both Hennessy and Watson (1994) and Kraemer *et al.* (1995) utilized different strength training intensities (5RM and 10RM, and 70-105% 1RM respectively) than the current study. Sequence of training was also different in both training studies. Kraemer and colleagues (1995) sequenced aerobic training 5-6 hours after strength sessions while Hennessy and Watson (1994) utilized both same and alternate day training.

Differences in MTRL between recovery conditions are likely due to different levels of fatigue in the muscle. Muscular fatigue is defined as the point at which a particular force level can no longer be maintained (Green, 1990) and may be affected by increases in $H^+$ due to lactic acid dissociation, decreases in energy substrates, decreases in neural drive, and structural damage (Green, 1990; Wenger & Reed, 1976; Edman, 1992). Without specific cellular and electrical measurements, it is difficult to determine the nature of the fatigue in both the 4 and 8-hour conditions. Speculation can be drawn from understanding of recovery periods of energy substrates and byproducts of exercise. Lactic acid removal from muscle has a half-time of approximately 25 minutes and levels should be returned to normal within 2 hours (Tesch, Colliander & Kaiser, 1986; Fox, Bowers & Foss, 1993). Therefore it is unlikely that hydrogen ions associated with lactic acid dissociation, are of sufficient concentrations in the muscle to impair force production. The ability of a muscle to contract also depends on the availability of energy substrates. Both phosphocreatine (PCr) and muscle glycogen are readily used as energy supplies for contracting muscles. PCr stores are completely restored within 5 minutes of cessation of training (Fox *et al.*, 1993) and it is unlikely that they are a cause for decreased strength performance following aerobic training. Glycogen, however, can take between 24 and 48 hours to return to resting levels following exhaustive exercise and the rate at which it is replenished largely depends on the timing and amount of carbohydrate ingested (Sherman, 1992). Strength training following both 4 and 8-hour periods of recovery would have been performed under conditions of reduced muscle glycogen levels. However, it is unclear whether or not this would have impaired muscular performance. If only 20-40% of muscle glycogen is utilized in a strength training session (Tesch *et al.*, 1986; Robergs *et al.*, 1991; MacDougall *et al.*, 1999), it would seem that levels exceeding this would provide sufficient energy substrate. It is possible however, that lower glycogen or other factors resulting from fatigue may affect the rate at which glycogen can be hydrolyzed.

Kent-Braun (1999) demonstrated that during a sustained contraction, neural drive contributes approximately 20% of fatigue experienced in the muscle. If prior aerobic training somehow reduces the ability of the central component to drive the muscle, it would be expected that strength performance would be impaired. Kroon and Naeije (1988) demonstrated that exhaustive exercise of the biceps muscles evoked long lasting impairments in muscle performance coinciding with decreased EMG for up to 25 hours.

It is possible that aerobic training in the present study had decreased ability of the central component to drive the muscle and therefore lower MTRL were performed.

Non-physiological factors may play a role as well in the observed reduced MTRL. It is possible that participants were mentally not prepared to do strength sessions following aerobic training on the same day. With less rest between sessions, participants may not be able to push themselves as much as they can with longer rest periods. Although instructed to go to fatigue, it is possible that participants volitionally quit 1-2 repetitions early. To consider this factor, participants were asked to rate their readiness to work on a scale from 1 to 10 (1=not at all; 10=maximal performance). Although not statistically analyzed, the 4-hour recovery condition (6.7) was lower on average compared to the control, 8-hour and 24-hour conditions (7.7, 7.5, 7.7, respectively). This suggests that a psychological component may have contributed to the observed decreased MTRL in the 4-hour recovery condition.

These results should also be viewed from a training perspective. Although a statistically lower MTRL occurred with 8 hours recovery from the control, it is questionable whether or not a loss of 4 repetitions over 4 sets will have a lesser training effect on strength improvements over the course of a training period. However, it is probable that a decrease of 12 repetitions in MTRL between the control and 4 hour recovery conditions might result in differences in strength improvements. Although, no effect was seen on MTRL by type of aerobic training, a greater amount of aerobic work can be performed when utilizing submaximal intensities. This is likely due to different fatiguing mechanisms of both maximal and submaximal aerobic training. It would seem then that athletes and coaches, as well as those examining the effects of concurrent training, should take care to allow sufficient rest when scheduling concurrent strength and aerobic training sessions.

## Conclusions

- Acute strength performance as measured using volume of work, can be impaired for up to 8 hours following high intensity interval training (85-100% POCMAP) and sub maximal continuous training (~70% POCMAP).
- This impairment is limited to the muscles used in prior aerobic training.
- Significantly more strength work can be performed when recovery time from aerobic training is increased from 4 to 8 hours.
- 24 hours appears to be enough recovery time to restore strength performance when performing 4 sets of an exercise.
- The impairment does not appear to be affected by the type of aerobic training

## Future Research Questions

1. Do fewer repetitions per workout as a result of fatigue result in compromised strength improvements over the course of a training program?
2. What physiological mechanism is responsible for the fatigue seen in muscles performing strength training following aerobic training?
3. What influences does training background have on the volume of strength work that can be done following aerobic training?
4. Would different aerobic training protocols produce different results?
5. Would high intensity aerobic training have a similar effect on different strength training protocols?
6. Would submaximal aerobic training have a similar effect on different strength training protocols?
7. Why are similar results observed between high intensity aerobic training and submaximal aerobic training?
8. Would both MAX and SUB protocols show similar results if total aerobic work were equated?
9. Is the response shown similar between males and females?

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# Appendix A

## Review of Literature

## Introduction

Many athletes are required to train for both muscular strength and aerobic power during the same training phase. This is often referred to as concurrent training (Leveritt, Abernethy, Barry, & Logan, 1999). Research on the effects of concurrent training has produced varied results. Differences in study design, including quality, quantity, and frequency of strength and aerobic training programs, order of training, and length and type of recovery periods between training sessions, could have led to these differences. However, it is often accepted that concurrent training results in impaired strength gains (Leveritt *et al.*, 1999; Chromiak & Mulvaney, 1990). Leveritt and colleagues (1999) suggest one possible reason for interference of strength gains is that of acute muscular fatigue. The fatigue hypothesis suggests that under concurrent training conditions, the amount of work that can be performed in each strength training session is reduced due to fatigue from prior aerobic training (Leveritt *et al.*, 1999). The purpose is to review the literature on concurrent training, discuss the effects of different strength and aerobic training protocols, examine the fatigue hypothesis and possible mechanisms of muscular fatigue, and discuss how these mechanisms may be involved in concurrent training.

## Concurrent Training

An athlete is deemed to undertake concurrent training when he/she is training for both muscular strength and aerobic fitness during the same training phase (Leveritt *et al.*, 1999). Currently, concurrent training research has produced inconclusive results. Some studies have shown that muscular strength and power is impaired while aerobic fitness is not (Hickson, 1980; Dudley & Djamil, 1985; Hunter *et al.*, 1987; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Bell, Syrotuik, Martin, Burnham, & Quinney, 1999). Other studies have demonstrated no impairment in muscular strength (Sale, MacDougall, Jacobs, & Garner, 1990; Bell, Pedersen, Wessel, Bagnall, & Quinney, 1991; Abernethy & Quigley, 1993; McCarthy, Agre, Graf, Posniak, & Vailas, 1995; Bell, Syrotuik, Socha, Maclean, & Quinney, 1997) and a single study has shown inhibition of aerobic power development (Nelson, Arnall, Loy, Silvester, & Conlee, 1990). Differences between studies in protocols for both strength and aerobic training, sequence of training, and duration of recovery periods between aerobic and strength training may affect the extent to which muscle is fatigued (Leveritt *et al.*, 1999). This may be one of the factors responsible for differences in results between studies.

## Concurrent Training – Strength Gains Impaired

Hickson (1980) demonstrated that over 10 weeks of training, concurrent training resulted in impaired maximal strength (1RM) of a parallel squat when compared to strength training only. Strength training was performed 5 days per week using multiple sets of multiple repetitions at approximately an 80% 1RM load. Aerobic training consisted of interval training on a cycle ergometer alternating daily with continuous running for a total of 6 sessions per week. Five intervals were performed at a workload that approached $\dot{V}O_2$ max with each 5-minute interval separated by 2 minutes of rest on interval days while continuous training consisted of running as fast as possible for 40 minutes. Concurrently trained subjects performed both protocols with normally 2 hours of rest separating aerobic and strength training when on the same day. Both groups improved strength at approximately the same rate up until week 7 of training, after which, the strength only group continued to increase while the concurrent group saw decreases in maximal strength. No differences were seen in $\dot{V}O_2$ max between the concurrent training and aerobic training groups. It was concluded that although concurrent training appears to have no affect on improvements in $\dot{V}O_2$ max, it does result in impaired strength improvements when compared to strength training alone. It is possible that the high volume of training may have resulted in an over fatigued state in the latter stages of the study. In an effort to minimize this possibility, Dudley and Djamil (1985) re-examined the effects of concurrent training utilizing lower training volumes. Strength training was performed on an isokinetic device 3 times per week using 2 sets of 30-second knee extensions at a velocity of 4.19 $rad \cdot sec^{-1}$ on alternate days. Aerobic training consisted of cycling between 40 and 100% $\dot{V}O_2$ max for 5 bouts of 5 minutes separated by 5 minutes of recovery. Strength and aerobic training were performed on alternate days for concurrent training group. Concurrent training resulted in improvements in peak torque at speeds of 0.00, 0.24, and 1.68 $rad \cdot sec^{-1}$ only while strength only training showed increases in peak torque at 0.00, 0.24, 1.68, 2.51, 3.35, and 4.19 $rad \cdot sec^{-1}$. Researchers concluded that concurrent training resulted in impairments to strength, however, only at high velocities ($> 1.68$ $rad \cdot sec^{-1}$).

Findings of Hennessy and Watson (1994) further support these conclusions and also suggest that strength impairments are specific to the muscle groups used in aerobic training. Over 8 weeks of training, the concurrent group performed strength training 1 day per week, aerobic training 2 days per week, and both strength and aerobic training twice per week. On days when both strength and aerobic training were performed, it is unclear as to which preceded the other. Strength training was designed in a periodized fashion using loads between 70 and 105% 1RM, repetitions between 1 and 10, and sets ranging from 3 to 6. Aerobic training consisted of three sessions of continuous running between 70 and 85% of age predicted maximum heart rate and one session of fartlek running. Concurrent training resulted in compromised development of lower body but not upper body strength. The concurrently trained group increased back squat 1RM by 5.4% while the strength only group increased by 16.7%. Concurrent training had no affect on improvements in $\dot{V}O_2$ max. Furthermore, the strength group also improved vertical jump and 20-m sprint time while the concurrent group did not. In addition to strength impairment being localized to the muscles used in aerobic training, concurrent training also appears to affect high velocity power movements. These findings are in agreement with those of Dudley and Djamil (1985).

Other researchers have shown that concurrent training impairs development of muscular power (Hunter *et al.,* 1987; Kraemer *et al.,* 1995; Bell *et al.*, 1999), however, their findings are not clear with respect to the development of strength. Hunter and colleagues (1987) demonstrated that subjects performing concurrent training were found have impaired increases in vertical jump when compared to those training only for strength even though improvements in 1RM bench press and squat were similar. Strength training was performed 4 times per week and consisted of 3 sets of 7 to 10 repetitions. Aerobic training consisted of running at 75% heart rate reserve (HRR) between 20 and 40 minutes 4 times per week. Concurrent training included two days per week when both aerobic and strength training were performed on the same day with strength training following aerobic training. The length of time between strength and aerobic training sessions on these days is not clear. The remainder of both strength and aerobic workouts were performed on alternate days. Although the authors reported that strength was not compromised by concurrent training, further analysis of the data by Leveritt and colleagues (1999) suggest that the effect size of strength improvements observed with strength training only was nearly double that of improvements under concurrent training conditions. As well, compromised vertical jump improvement was not seen in an additional concurrent group of previously aerobically trained participants suggesting that level of aerobic fitness may affect the extent to which concurrent training compromises strength and power gains.

Kraemer and colleagues (1995) reported that concurrent training may affect both strength and power and that these effects are limited to the muscle groups utilized in aerobic training. Training was performed 4 days per week with strength training performed at 8:00am in the morning and aerobic training occurring between 5 and 6 hours later. Strength training was a split routine with one light day (3 sets of 10RM; Mon and Thurs) and one heavy day (5 sets of 5RM; Tues and Fri) and consisted of full body exercises. The same muscle groups were trained in each strength training session. Aerobic training consisted of both continuous running (40 min @ ~ 80-85% $\dot{V}O_2$ max; Mon and Thurs) and interval sprint training (95-100% $\dot{V}O_2$ max for 200-800m; Tues and Fri). Training lasted 12 weeks and participants were divided into 4 groups; strength only (S), concurrent strength and aerobic (C), concurrent upper strength only and aerobic (CU), and aerobic only (A). Both S and C increased maximum leg press strength and the % improvement was significantly greater in S. Unfortunately pre and post values are not included, however, figures indicate that C had a larger pre leg press value and that absolute improvements for both groups are similar. This may account for the larger relative improvements in S. Upper body strength was not impaired with concurrent training, supporting the notion that compromises in strength are limited to the muscles used in aerobic training. As well, only S improved in peak leg power leading the authors to conclude that concurrent training may compromise power development of the legs.

Bell and colleagues (1999) demonstrated that observed impairment of strength might vary depending on the measure used in evaluation. Using two different measures of lower body strength, concurrent training was shown to both compromise and not effect strength improvements. Strength training was performed 3 times per week and consisted of 2-6 sets of 4-12 repetitions at a variety of intensities. Aerobic training was also performed 3 times per week with continuous training (30-42 minutes @ ventilatory threshold (VT)) done twice and interval training (4-7 sets of 3min work/3min recovery @ ~ 90% $\dot{V}O_2$ max power output) done once. Increases in maximal unilateral, leg extension strength under concurrent training conditions were compromised when compared to strength training alone, however, maximal leg press improvements were not. The authors concluded that was due to greater movement similarities between cycling and unilateral leg extension than between cycling and leg press. This might be too simplified, as the pedal stroke in cycling is multi-joint, where as leg extension is single joint. Furthermore, force is applied in a direction that is more similar to a leg press than a leg extension. The authors' final conclusion that concurrent training inhibits strength development is not completely warranted. This highlights the importance of measurement selection when examining the effects of concurrent training.

Under certain conditions concurrent training appears to compromise development of muscular strength and power. What conditions attenuate impairment are difficult to interpret, however, it does appear that this impairment is localized to the muscle groups utilized in aerobic training. Furthermore, muscular power seems to be affected to a greater extent than muscular strength.

## Concurrent Training – Strength Gains Not Impaired

Sale and colleagues (1990) were the first to show that strength development is not compromised when undertaking concurrent training. Two groups were used to compare the affects of concurrent training on both strength and aerobic development. One group performed concurrent training with one leg and strength training with the other (CS) while the other group performed concurrent training with one leg and aerobic training with the other (CA). Strength training consisted of 6 sets of leg press at 15 to 20RM with 2 minutes rest between sets while aerobic training consisted of 5, 3-minute intervals at 90-100% $\dot{V}O_2$ max on a cycle ergometer. For concurrently trained legs, aerobic training always preceded strength training with no recovery periods between the two. There was no difference in increases in maximal leg press between each leg in CS while CA showed similar improvements in $\dot{V}O_2$ max between each leg. Over 22 weeks, neither strength nor aerobic power improvements were compromised in the legs performing concurrent training. Number of repetitions that could be performed at 80% 1RM was greater in concurrently trained legs than strength only trained legs suggesting an attenuation of sub-maximal strength with concurrent training. These results are supported by those of Abernethy and Quigley (1993). Using the triceps brachii they demonstrated that over 7 weeks, maximal isokinetic strength at 30° from full extension (T30) at speeds between 0.52 to 5.20 rad•sec$^{-1}$ was not impaired when compared to strength training alone.

Strength training consisted of 2 sets of 30-second isokinetic elbow extensions at a speed of 4.16 rad•sec$^{-1}$ while arm cranking was used for the aerobic training (5 x 5min bouts @ 40-100% $\dot{V}O_2$ max). Concurrent training was performed on the same day with strength training preceding aerobic training by at least 2 hours. One day separated each training session. Both strength and concurrent training groups resulted in similar increase in peak torque at T30 and $\dot{V}O_2$ max. These results are in conflict with those of Dudley and Djamil who demonstrated impaired strength performance in the quadriceps at higher contraction speeds. In the present study, the majority of the improvements in strength came in the first 2 weeks with little improvement over the last 5. The authors suggested that different strength development patterns for the triceps brachii and quadriceps are possible and this may lead to the differing affects of concurrent training on isokinetic strength. This does not seem logical. Rather, differences may have been due to different concentrations of fiber types between the two muscle groups and therefore the triceps brachii were not susceptible to compromised strength or power development with concurrent training.

McCarthy and colleagues (1995) also demonstrated that concurrent training does not compromise strength or aerobic power. Training lasted 10 weeks with both strength and aerobic training sessions being performed on the same days, 3 times per week. Order of strength and aerobic training alternated with less than 20 minutes of rest separating the two training sessions. Strength training consisted of 3 sets of 6RM of eight different isotonic exercises while aerobic training was continuous cycling (50 min) at approximately 70% of HRR. Both strength and concurrent training groups showed similar increases in isometric strength, isotonic strength (squat and bench press), and vertical jump while neither group improved isokinetic strength. $\dot{V}O_2$ max was not compromised by concurrent training. Authors suggest that reduced overall volume of concurrent training (3 days vs. 5 or 6) may explain the differences in strength and power development when compared to other concurrent training studies. As well, the type of strength training (isotonic) may be responsible for differences in isokinetic strength improvement when compared to the results of Dudley and Djamil (1985) and Abernethy and Quigley (1993). It appears that strength and power development may not be compromised with concurrent training.

Bell and colleagues (1997) demonstrated that the effects of concurrent training might be affected by gender. Concurrent training for 16 weeks resulted in compromised strength improvements in females when compared to strength training only but not in males. Strength training followed a periodized plan consisting of 2 to 6 sets of 2 to 10 repetitions using a variety of full body, isotonic exercises, performed 3 times per week. Aerobic training was also performed 3 times per week on alternate days with strength training and consisted of both continuous and interval training on a rowing ergometer. Continuous training was performed twice per week at a heart rate corresponding to ventilatory threshold for 30-45 minutes. Intervals were divided into 3 minutes work, with heart rate at approximately 90% $\dot{V}O_2$ max, followed by 3 minutes of active recovery for 5 to 8 sets. Maximal leg and bench press strength was tested at 4-week intervals throughout the study. Of both measures for males and females, only improvements in leg press for females was statistically different between concurrent and strength training groups. Similar to the findings of McCarthy and colleagues (1995) and Hennessy and Watson (1994), compromises in strength due to concurrent training are not associated with muscle groups that are used minimally in aerobic training. Although the back muscles and biceps are recruited during the pull phase of the rowing stroke, the chest and triceps do little work. Perhaps if a different measure of upper body strength was used (lat pull down), strength impairments might have been seen. The authors also suggest that males and females respond differently to concurrent training as males showed similar improvements in strength measures between concurrent training and strength training while women did not. However, compromised strength in the females might also be due to a lower initial leg press strength in the strength group than in the concurrent group (67.1 kg less). Perhaps the concurrent group was closer to their genetic ceiling and therefore improvements in strength were more difficult to attain. Furthermore, a non-random assignment was used resulting in rowers making up the concurrent group and university students (non-rowers) making up the strength group. It is difficult to compare different training protocols between 2 populations with different training backgrounds.

It appears that concurrent training can be performed without improvements in strength being compromised.

## **Concurrent Training – Compromised Aerobic Power Gains**

Only one study to date has shown that concurrent training results in compromised improvements in aerobic power with no affect on strength improvements. Nelson, Arnall, Loy, Silvester, and Conlee (1990) demonstrated that concurrent training for longer than 11 weeks resulted in no further improvements in $\dot{V}O_2$ max in untrained male subjects. Strength training consisted of 3 sets of 6 maximal isokinetic knee extensions at 0.52 rad•sec$^{-1}$, 4 days per week. Aerobic training was performed on a cycle ergometer for 30 to 60 minutes at 75-85% maximum heart rate 4 times a week also. Both strength and aerobic training were performed on the same day, with strength always performed immediately before aerobic training. Both concurrent training and aerobic training alone resulted in similar increases in $\dot{V}O_2$ max over the first 11 weeks, however, from weeks 11 to 20, only the aerobic training group continued to show improvement (4.7 vs. 1.1 $ml \cdot kg^{-1} \cdot min^{-1}$ for the aerobic and concurrent groups respectively). Peak torque, measured at 30°, 60°, and $180° \cdot sec^{-1}$, was significantly improved in both concurrent and strength only groups and values were not different between groups. These results are in contradiction to those of Dudley and Djamil (1985), Hickson (1980), and others, however, this contradiction may be due to the order of training. Nelson and colleagues sequenced strength training always immediately before aerobic training. This may have allowed for a less fatigue state during the strength training sessions. It has been shown that strength training results in increases in both muscle and blood lactate (Tesch, Colliander, & Kaiser, 1986; MacDougall, Ray, Sale, McCartney, Lee, & Garner, 1999; Abdessemed, Duche, Hautier, Poumarat, & Bedu, 1999). The resulting changes in pH due to increased $H^+$ has been associated with muscular fatigue (MacDougall *et al.*, 1999; Abdessemed *et al.*, 1999). Aerobic training immediately following strength training may be compromised due to increased acidity in the muscle. The similar increases in $\dot{V}O_2$ max during the first 11 weeks may be due to the relatively low initial $\dot{V}O_2$ max scores of both groups. As aerobic power increased, a higher training intensity would be needed to elicit further improvements. Decreased pH levels prior to aerobic training would make it more difficult to attain and maintain the higher intensities necessary for further aerobic power increases. It appears that although strength improvements are not affected when strength training immediately precedes aerobic training, improvements in $\dot{V}O_2$ max may be compromised. Longer recovery periods and/or training on alternate days may limit this impairment.

## Adaptations to Strength Training

Improvements in muscular strength, as measured by the force produced during a maximal voluntary contraction (MVC), occur as a result of an increase in muscle cross-sectional area (CSA) and the ability to effectively activate motor units (Sale, 1992). The increase in cross-sectional area of muscle is considered to occur as a result of protein synthesis, primarily actin and myosin in the myofilaments, which produces a greater number of contractile units (Goldspink, 1992). Enhanced motor unit activation (MUA) results from a greater number of fibers being recruited, increased firing frequency, decreased co-contraction of antagonists, better synchronization of MUA, and inhibition of reflexive mechanisms (such as the golgi tendon organ) that normally govern the amount of force that can be generated (Sale, 1992; Wilson, 1994). Increases in muscle cross-sectional area typically result in an increased body mass and are important in developing absolute strength. Programs designed to enhance MUA are usually aimed at improving relative strength, or strength relative to body mass (Fleck and Kraemer, 1997).

Increases in MVC have been produced through a variety of training protocols, primarily manipulating the training variables of intensity (load or resistance) and volume (number of repetitions). There is an inverse relationship between the weight that is lifted and the number of repetitions to produce muscle failure.

## Training Protocols Designed to Promote Muscle Hypertrophy

It has been suggested that protein synthesis is stimulated by stressing the muscle energy systems to produce a significant displacement from rest (Houston, 1999). A variety of training loads and subsequent repetitions have been found to increase the CSA of muscle. Muscle hypertrophy has been shown to occur in subjects training with loads of 6RM or greater (Schott, McCully, & Rutherford, 1995; Davies *et al.*, 1988) however, greater increases in CSA have been found to occur with 8-12 RM loads (Naricci & Keyser, 1994; Naricci et al, 1989; McCall *et al.*, 1996; Kawakami *et al.*, 1995; Houston, 1999). Although lighter RM loads (12-15RM) have been found to increase CSA (Jackson, Dickinson, & Rinal, 1990), Sale and MacDougall (1981) and Arnett (1993) suggested the hypertrophic response decreases as the load becomes lighter and the number of repetitions extends beyond 15. Consequently most practitioners have recommended training at 8-12 RM loads in order to induce muscle hypertrophy (Poliquin, 1991; King, 1998; Schmidbleicher, 1985). In addition, muscle hypertrophy is also optimized when there is sufficient training volume and there are multiple exercises per muscle group (Baker *et al.*, 1994).

## Training Protocols Designed to Promote MUA

Training at higher loads (4-6RM) has resulted in increased MVC in the absence of significant muscle hypertrophy (Schmidtbleicher & Buehle, 1987). Such increases in force generation are attributed to neural adaptations that include increased MUA, faster firing frequency of motor units, improved synchronization, and decreased co-contraction of antagonists (Sale, 1992). Kraemer, Fleck and Evans (1997) suggested that as the training stimulus promotes an increase in CSA, the contributions from the neural mechanisms to force production diminish. However, if the training stimulus is of insufficient volume to stimulate hypertrophy, greater neural adaptations occur. Schmidtbleicher and Buehle (1987) showed that although both low and high intensity strength training resulted in similar increases in MVC (21% and 18%, respectively), the contributions from neural adaptations and muscle hypertrophy were different between the two loading intensities. High intensity training resulted in a greater rate of force development, considered to reflect neural adaptation (34% compared to 4%), whereas low intensity training (~10-12RM) resulted in a greater increase in muscle size (7% compared to 3%). Hakkinen, Komi, Alen, and Kauhannen (1987) also showed that high intensity training resulted in greater neural adaptation as reflected by increased EMG activity. Chestnut and Docherty (1999) however, did not confirmed this. They demonstrated similar neuromuscular adaptations in subjects training at 4RM and 10RM loads over 10 weeks of training. Both training protocols elicited similar increases in strength, cross-sectional area, and specific tension. Untrained subjects were used in this study and it has been suggested that early on in training (up to 10 weeks), strength gains are primarily due to neural factors regardless of the training protocol, with muscular hypertrophy playing more of a role beyond this point (Fleck & Kraemer, 1997).

Currently, few studies examining concurrent training implement similar strength training protocols. Due to distinct responses to different training protocols it is possible that conflicting data may result from differences in strength training programs.

## Adaptations to Aerobic Training

Most studies investigating concurrent training have focused on developing $\dot{V}O_2$ max. Consequently, discussion will be limited to the relationship between different training protocols and the development $\dot{V}O_2$ max. A variety of training protocols have been found to increase $\dot{V}O_2$ max, including different levels of training intensities (Fox *et al.*, 1975; Eddy, Sparks, & Adelia, 1977; Dudley & Djamil, 1985; Wenger & Bell, 1986). However, training at different intensity levels appears to produce different physiological adaptations. Craig, Lucas, Pohlman, and Stelling (1979) showed a 12% increase in aerobic power from training at approximately 65% $\dot{V}O_2$ max whereas Cunningham, McCrimmon and Vlach (1979) showed significant increases in aerobic power training at both 80% and 100% $\dot{V}O_2$ max. Wenger and Bell (1986) suggested that greater improvements occur in aerobic power as training intensity approaches $\dot{V}O_2$ max.

Depending on the intensity of training, adaptation may occur in either the central (heart, lungs, and circulation) or peripheral (within the muscle) components. At lower intensities, the physiological adaptations occur primarily in the central component (Cunningham *et al.*, 1979; MacDougall & Sale, 1981). MacDougall and Sale suggested that maximal contractile forces of the heart occur at approximately 75% $\dot{V}O_2$ max, and consequently the optimal training stimulus for enhancing the cardiopulmonary system would be at an intensity slightly below anaerobic threshold (70-80% $\dot{V}O_2$ max). Cunningham et al. compared continuous (80% $\dot{V}O_2$ max) and interval (100% $\dot{V}O_2$ max) training using untrained female subjects. Although both groups showed significantly similar improvements in $\dot{V}O_2$ max, the interval group demonstrated greater increases in a-$vO_2$ difference than the continuous group, reflecting greater peripheral adaptation. The improvement elicited by the continuous group would have been more centrally mediated.

It has been proposed that peripheral adaptations are stimulated through a state of hypoxia experienced by the muscle during high intensity, aerobic interval training (MacDougall and Sale, 1981). Adaptations include increases in muscle capillarization, mitochondrial enzyme activity and concentration, and myoglobin (Mb) content (Hollozy and Coyle, 1984; Hoppeler *et al.*,1985). Several studies using near infrared spectroscopy (NIRS) have shown that the degree of muscle hypoxia is directly related to the increase in exercise intensity (Bhambhani, Buckley, & Susaki, 1997; Bellardinelli *et al.*, 1995; Bhambhani *et al.*, 1999). Higher exercise intensities have also been associated with a shift in fiber-type recruitment and adaptation. Dudley, Abraham, and Terjung (1982) measured Cytochrome C concentrations in mice after 8 weeks of training at various intensities. As intensity increased so did adaptations in both type I and IIa fibers along with increases in the oxidative capacity of IIb fibers. At higher intensities, only type IIb fibers showed further increase in oxidative capacity.

It appears that the type of physiological adaptation is dependent on the intensity of aerobic training. Currently, few studies examining concurrent training implement similar aerobic training protocols. Due to distinct responses to different training protocols it is possible that conflicting data may result from differences in aerobic training programs.

## Fatigue Hypothesis

It is suggested that impaired strength gains may be due to increased fatigue of the muscle (Leveritt *et al.*, 1999; Craig *et al.*, 1991; Sale *et al.*, 1990). This fatigue hypothesis (Leveritt *et al.*, 1999; Craig *et al.*, 1991) states that under concurrent training conditions, the amount of work that can be performed in each strength training session is reduced due to fatigue from prior aerobic training (Leveritt *et al.*, 1999). Understanding that total work is an important factor in optimizing the strength training response (Fleck & Kraemer, 1997), a reduction in work may compromise training adaptations. It is not clear however, whether or not this would result in compromised strength improvements over the course of a training program. Both the sequence of training and the amount of recovery between training sessions affect fatigue state and therefore may affect the quality of strength training (Leveritt *et al.*, 1999). Modifications to either one of these training variables might affect the extent to which strength improvements might or might not be compromised.

### Sequence of Training

Bell, Stewart, Petersen, Quinney, and Wenger (1988) have shown that over a 5-week training period, subjects performing aerobic training prior to strength training experienced compromised gains in high-velocity strength when compared to those who performed strength training first. In both conditions, one training session immediately followed the other. Using a sub-maximal training intensity for aerobic training (75% $VO_2$max), and a combination of 12 hydraulic resistance exercises (2 sets of 20 seconds at

~ 3.0 rad•sec$^{-1}$), peak torque significantly improved at high velocities only in the group performing strength training prior to endurance training. It is possible that maximal intensity aerobic training might result in a greater compromise of strength than that observed in the current study. Since a control group was not used, one is unable to determine if strength improvements were not compromised in the group performing strength training first. However, strength improvements appear to be compromised when aerobic training precedes strength training.

In concurrent training research in which strength and aerobic training are performed on the same day, sequence of training is not often consistent between studies. This makes comparison of results between two or more studies difficult. When aerobic training precedes strength training, there have been varied results in both muscular strength and power improvements (Hickson, 1980; Kraemer *et al.*, 1995; Sale *et al.*, 1990). Conflicting results indicate that strength improvements can be both compromised (Hickson, 1980) and unaffected (Kraemer *et al.*, 1995; Sale *et al.*, 1990). Similarly, gains in muscular power have been both impaired (Kraemer *et al.*, 1995) and uncompromised (Sale *et al.*, 1990) when compared to strength training alone. However, when strength training precedes aerobic training, strength improvements appear not to be compromised (Abernethy & Quigley, 1993; Nelson *et al.*, 1990). The extent to which muscular strength and power is affected appears to be related to the sequence of same day training. This is in agreement with the conclusions of Bell and colleagues (1988). There are studies, however, that perform strength and aerobic training on alternate days. Alternate day training allows for increases in the length of recovery time between training sessions. The effects of training on alternate days appears to have minimal impairments on strength improvements at low speeds (Dudley & Djamil, 1985; Bell *et al.*, 1997) but may compromise improvements in muscular power (Dudley & Djamil, 1985). It is difficult to interpret the results of sequence of training in other studies due to combinations of same and alternate day training (Hennesy & Watson, 1994; Hunter *et al.*, 1987) or variations in sequence of training (McCarthy *et al.*, 1995). It appears though that when strength training is performed following aerobic training and not on alternate days as aerobic training, strength and power improvements may be compromised. These compromised gains may be due to acute fatigue experienced by the muscle and the its compromised ability to perform work in a subsequent strength training session (Abernethy, 1993; Leveritt & Abernethy, 1999). To limit the amount of fatigue, enough time must be allotted to ensure adequate recovery of the working muscles during concurrent training.

## Length of Recovery Period between Aerobic and Strength Training

A few studies have looked at the acute effects of prior aerobic training on subsequent strength training performance (Abernethy, 1993; Leveritt & Abernethy, 1999; Sale et al., 1990). Abernethy (1993) showed impaired isokinetic strength performance at a variety of speeds, when both long slow duration (LSD) and interval (INT) aerobic exercise were performed 4 hours prior. LSD consisted of 150 minutes cycling at ~ 35% $\dot{V}O_2$ max while INT included 5 bouts of 5 minutes (40, 60, 80, 100, 100% $\dot{V}O_2$ max) separated by 5 minutes of passive recovery. Isokinetic leg extensions were used to measure strength at 10 contractile speeds between 0.52 and 5.20 rad•sec$^{-1}$. A main effect was shown in peak strength from pre to post aerobic training and this effect was similar for both LSD and INT. No effect was seen with respect to contractile speed. They concluded that although decreased performance in isokinetic strength occurred, it is not possible to determine whether or not this would result in compromised strength over the course of a training program. Leveritt and Abernethy (1999) have provided further support for the acute effects of aerobic exercise on subsequent strength performance. High intensity interval training, 5 bouts of 5 minutes (40, 60, 80, 100, 100% $\dot{V}O_2$ max) separated by 5 minutes of passive recovery, impaired both isokinetic and isoinertial strength (squat) 30 minutes post aerobic exercise and isoinertial strength was more affected than was isokinetic strength. As well, the number of repetitions performed in all sets of the subsequent squat exercise was significantly reduced. Strength training programs often utilize isoinertial exercises (squat, leg press, and bench press) as opposed to isokinetic training devices, as well as two to four exercises per muscle group. It is possible that a greater impairment may occur in the latter exercises of a training session, further decreasing the ability to perform work. Thus it seems that both sub-maximal and maximal aerobic training, when performed prior, compromise strength performance in a subsequent strength training session.

The length of recovery period between aerobic and strength training either varies or is unclear in studies examining the effects of concurrent training. However when strength precedes aerobic training or when the two are performed on alternate days, improvements in strength have not been compromised (Dudley & Djamil, 1985; Bell *et al.*, 1997; Abernethy & Quigley, 1993; Nelson *et al.*, 1990). It could be assumed that under these conditions, the recovery period prior to strength training would be much longer, ranging between 12 and possibly more than 24 hours. This might help explain conflicting results between concurrent training studies.

Only one training study specifically compares concurrently trained groups with different periods of recovery between strength and endurance training sessions. Sale and colleagues (1990) compared the effects of strength and aerobic training on the same day with alternate days. Both groups were prescribed identical strength and aerobic training protocols. It is not clear as to the time between training sessions when performed on the same day. Aerobic training consisted of 6 to 8, 3-minute intervals separated by 3-minute rest periods. Training intensity was 60, 80, and 90-100% $\dot{V}O_2$ max for the first, second, and all subsequent intervals respectively. Strength training was performed on a leg press machine for 6-8 sets of 15-20 repetitions with 2 minutes rest between sets. The first three sets were used as a warm-up while remaining sets were performed with a load resulting in concentric failure within the desired number of repetitions. Although training programs were the same, the group training on alternate days showed significantly greater improvements in maximal leg press strength than those training on the same day at both 10 and 20 weeks (18% and 25% versus 7% and 11%). Furthermore, average training volume for each strength training session was significantly lower for the same day training group even though the sequence of endurance and strength training alternated each session. The authors concluded that concurrently training both strength and endurance on the same day impaired strength gains and that this was possibly due to a decrease in average volume per strength training session. No control group was used to verify if strength gains were compromised in the group training on alternating days. However, it appears that 24 hours of recovery following endurance training results in improved ability of the muscle to perform work as compared to 30 minutes (Sale et al., 1990). Abernethy (1993) suggested that this impairment lasts at least 4 hours. As yet, a time frame for the optimum recovery period for subsequent strength training has not been determined.

## Muscular Fatigue

The extent to which any given physical activity can be performed is limited by the onset of muscular fatigue (McLester, 1997). Muscular fatigue is defined as an exercised induced reduction of the capacity to generate force or power (Vollestad, 1997). More specifically in strength training environments, muscular fatigue is referred to as the point at which a particular force level can no longer be maintained (Green, 1990). A muscles ability to generate force is dependent on the attachment of cross-bridges between myofibril proteins, actin and myosin. Therefore, impairment of this process will result in the expression of muscular fatigue.

Although an exact source of fatigue is difficult to pinpoint, it most likely results from a combination of several different mechanisms (Wenger & Reed, 1976; Green, 1990; Kent-Braun, 1999). The extent to which each is involved is dependant on the type of exercise being performed (Vollestad, 1997). These mechanisms may be either centrally or peripherally mediated (Green, 1990; Edman, 1992; Kent-Braun, 1999). Sources of central fatigue may include supraspinal failure, depression of motor neuron excitability, and pre-synaptic failure (Green, 1990; Edman, 1992). The ability to measure and differentiate between these sources is difficult and will not be discussed here, rather all will be considered as the central component. Peripheral sources of fatigue include increased $H^+$ concentration due to dissociation of lactic acid, limited energy substrate availability, ionic imbalances, and damage to the myofibril proteins themselves (Wenger & Reed, 1976; Green, 1990; Edman, 1992; Tesch *et al.*, 1986; Abdessemed *et al.*, 1999). Whether it is one of these factors or a combination of several, the end result is the inability of the muscle to produce the required level of force.

## Use of Energy Substrates in Strength Training

The ability of the muscle to generate force is driven by hydrolysis of the high-energy phosphate molecule, adenosine triphosphate (ATP) (Billeter & Hoppeler, 1992). ATP is produced in the muscle through both aerobic and anaerobic systems, however, anaerobic energy systems provide the majority of ATP utilized in strength training (Billeter & Hoppeler, 1992). Both the phospho-creatine (PCr) system and glycolysis have been shown to provide the energy needed during resistance training (Tesch *et al.*, 1986; Robergs *et al.*, 1991; MacDougall *et al.*, 1999).

Tesch and colleagues had subjects perform 5 sets of 5-10 repetitions for four different lower body exercises at a load that induced muscular failure in each set. Results indicate that both PCr and glycogen stores were significantly decreased post-strength training (~50% and 40% respectively). The authors suggested that because the biopsy was taken 30 seconds after completion of exercise, and that the half-time of PCr repletion is 30-40 seconds, it is likely that PCr stores were almost completely exhausted by the exercises. This led them to conclude that it is a combination of both PCr and glycogen that provides the energy required for strength training. Robergs and colleagues (1999) also reported that glycogen acts as a fuel source during strength training. Utilizing both

35% and 70% 1RM loads, they reported a significant decrease in the amount of glycogen and a corresponding increase in intra-muscular lactate levels. After 3 and 6 sets of 6 repetitions, glycogen levels were reduced by approximately 20 and 40% respectively, in both groups. Volume was equated between groups so that the group doing 35% 1RM loads performed as many repetitions as necessary to equal the force output of the group utilizing loads of 75% 1RM. It was concluded that, regardless of the load utilized, strength training places demands on glycogen stores for energy supply through glycolysis.

MacDougall and colleagues (1999) further demonstrated the importance of PCr and glycogen as sources of energy in strength training. Using slightly lower volumes than used by Tesch *et al.* and Robergs *et al.*, they demonstrated significant reductions in both PCr and glycogen stores. Muscular PCr and glycogen were measured and compared after both 1 and 3 sets of arm curls at 80% 1RM to fatigue. Results indicate that in both the 1- and 3-set conditions, PCr levels were reduced by 64 and 50% respectively. Glycogen levels however, were only significantly reduced (24%) after 3 sets. It was suggested that fatigue early on may be linked to PCr depletion while fatigue in latter sets might be due to factors associated with glycogenolysis.

## Energy Substrates as a Source of Muscular Fatigue during Concurrent Training

Both PCr and glycogen appear to be the primary energy suppliers during strength training (Tesch *et al.*, 1986; Robergs *et al.*, 1991; MacDougall *et al.*, 1999). It would be expected that a reduction in the ability of the muscle to extract energy from either of these substrates might result in muscular fatigue. Understanding that aerobic training can result in significant reductions in muscle glycogen (Sherman, 1992), it is possible that the onset of fatigue may result sooner in a strength training session following aerobic training. This may help explain impaired strength performances following prior aerobic training.

It is suggested that nearly 100% of PCr stores are replenished within 5 minutes (Fox, Bowers, Foss, 1993). Therefore it is unlikely that reduced PCr stores are a cause for decreased strength performance following aerobic training. Muscle glycogen levels however, may be suppressed for up to 48 hours following aerobic exercise and the rate at which it is replenished largely depends on the timing and amount of carbohydrate ingested (Sherman, 1992). Utilizing different strategies it is possible for depleted glycogen stores to be replenished in 24 hours (Sherman, 1992). Depending on length of recovery time between training sessions, strength training following aerobic training may be performed under conditions of reduced muscle glycogen levels. However, it is unclear whether or not this will impair muscular performance. If only 20-40% of muscle glycogen is utilized in a strength training session (Tesch *et al.*, 1986; Robergs *et al.*, 1991; MacDougall *et al.*, 1999), it would seem that levels exceeding this would provide sufficient energy substrate. It is possible however, that lower glycogen may affect the rate at which glycogen can be hydrolyzed.

Few researchers have examined the effects of glycogen depletion on strength performance. One study that has, demonstrated that strength performance following aerobic exercise might depend on the extent to which glycogen is depleted in different fiber types (Jacobs, Kaiser, & Tesch, 1981). Subjects experiencing glycogen depletion in both fast twitch (FT) and slow twitch (ST) fibers, showed a significant reduction in maximal strength and increased rate of fatigue for up to 2 hours post aerobic exercise when compared to pre-test values. However, subjects experiencing primarily ST fiber depletion showed only a significant increase in rate of fatigue while maximal strength was unaffected. This led the authors to conclude that although glycogen depletion is associated with impaired muscular performance, the expression of the impairment depends on the extent to which either FT or ST fibers are depleted. This supports the importance of using consistent training protocols when examining the effects of concurrent training. Sherman and colleagues (1984) however, showed that decreased muscle performance from prior aerobic exercise lasts longer than the time it takes to replenish glycogen stores. Subjects performing a marathon demonstrated decreased maximal peak torque for up to 7 days. This is much longer than the 24-48 hours needed to replenish glycogen stores suggested by Sherman (1992). Keizer and colleagues (1987) also supported this. They suggested that fuel replenishment is not solely responsible for muscular performance following fatigue. Using a graded cycle ergometer test, they showed that although glycogen stores were normalized 22 hours post fatigue, maximal physical working capacity was still reduced by approximately 7%.

The ability of the muscle to produce force is dependent on the production of ATP from both PCr and glycogen through anaerobic means. However, it appears unlikely that decreased stores of these two substrates is solely responsible for impaired strength performance following aerobic exercise.

## Decreases in Muscle pH in Strength Training

A byproduct of anaerobic glycolysis is lactic acid. At physiological pH, nearly 100% of lactic acid is in its ionized formed (Fox, Bowers, & Foss, 1993). Lactic acid dissociates in the muscle to produce lactate and hydrogen ions resulting in a decrease in muscle pH (Fox, Bowers, & Foss, 1993). Wenger and Reed (1976) suggest that the increase in $H^+$ ion in turn will impair several factors key to the production of force. Decreases in phoshofructokinase (PFK) activity, membrane permeability to $Na^+$ and $K^+$, and binding of calcium to troponin, all result from increased muscle acidity. It is difficult to obtain measures of $H^+$ in the muscle and due to their stochiometric relationship, lactate measures are often used as a representative measure of the amount of $H^+$ ion present. Although measuring and reporting lactate, it is the associated $H^+$ ion that is responsible for fatigue.

It is important when discussing lactate, to differentiate between blood and muscle lactate measures. Blood lactate measures represent the levels of lactate in the plasma and may be influenced by rates of production in the muscle, diffusion from muscle to the blood, and clearance from the blood. They are not necessarily representative of lactate levels in the muscle. Muscle lactate measures represent the concentrations of lactate in the muscle tissue, however are only attainable through biopsy sampling. Several studies have associated blood lactate responses with muscular fatigue in strength training (Brown *et al.*, 1990; Hannie, Hunter, Kekes-Szabo, Nicholson, & Harrison, 1995; Reynolds, Frye, & Sforzo, 1997; Larson Jr., & Potteiger, 1997; Abdessemed *et al.*, 1999). For purposes of this review, only studies utilizing muscle lactates will be examined due to difficulties of interpreting blood lactates as mentioned previously.

Strength training has been shown to increase levels of muscle lactate and these increases have been associated with muscular fatigue (Tesch *et al.*, 1986; Robergs *et al.*, 1991; MacDougall *et al.*, 1999). After 4 sets of a variety of lower body exercises performed to failure (6-12 repetitions), Tesch and colleagues (1986) showed a 5 fold increase in muscle lactate to 17.3 mmol•kg$^{-1}$ w.w. The authors concluded that muscle pH had dropped low enough to interfere with enzyme activity limiting the flux of energy production. Further more, it was suggested that decreases in power were due to a combination of several mechanisms being impaired by increased acidity. These included reduced Ca$^{++}$ availability, cross bridge formation, and PCr resynthesis. It should be noted that muscle biopsies were obtained after completion of the fourth exercise making it difficult to determine if muscle lactate levels were responsible for fatigue in earlier sets of earlier exercises. Robergs and colleagues found similar findings in muscle lactate using two different training loads (35% 1RM (L) and 70% 1RM (H)). Both groups showed significant increases in muscle lactate at both 3 and 6 sets to failure (L=13.0, H=11.7 and L=16.7, H=13.8 mmol•kg$^{-1}$ w.w respectively). When volume was equated using different loads, muscle lactate accumulation was similar, however, only H exercised to fatigue. Conclusions regarding muscle lactate and fatigue must therefore be limited to this group only. The authors also demonstrated that 2 hours of recovery was sufficient to return muscle lactate to resting levels in both groups. In comparison to the findings of Tesch and colleagues (1986), these findings suggest that after as few as 3 sets to failure, H$^{+}$ are sufficiently high enough to alter muscle pH.

MacDougall and colleagues (1999) demonstrated a significant increase in muscle lactate following a single set of resistance exercise. Using a load of approximately 80%

1RM, lactate levels increased from 7.3 to 91.4 mmol•kg$^{-1}$ d.w after 1 set of arm curls to fatigue. These increases were similar to levels obtained in a group performing 3 sets to failure (6. 2 to 118 mmol•kg$^{-1}$ d.w). The authors suggested that 3 minutes of recovery between sets was likely not enough for complete removal of lactate from the muscle, and therefore, each subsequent set began with elevated lactate and hydrogen ion levels leading to an earlier onset of fatigue.

## Lactate as a Source of Fatigue during Concurrent Training

It is possible under concurrent training conditions, if the recovery period from aerobic training is not of sufficient length, that the internal environment of the muscle may not be optimal for producing force resulting in decreased performance (Abernethy, 1993; Leveritt & Abernethy, 1999; Sale *et al.*, 1990). If hydrogen ion levels are even slightly elevated prior to strength training, a decrease in the number of repetitions performed may result due to an earlier onset of fatigue. Leveritt and Abernethy (1999) demonstrated that 30 minutes after a single bout of high intensity aerobic training blood lactate levels were significantly higher prior to performing strength training. Strength training under these conditions produced significantly fewer repetitions per set over 3 sets than with no prior aerobic training. These results should be interpreted with caution however, due to the uncertainty regarding blood lactate being representative of muscle lactate and therefore hydrogen ion concentrations.

It is suggested that lactic acid removal from muscle has a half-time of approximately 25 minutes and levels should be returned to normal within 2 hours (Tesch *et al.*, 1986; Fox, Bowers, Foss, 1993). Recovery periods following aerobic training of greater than 2 hours should therefore minimize the effect of elevated hydrogen ions in a subsequent strength training session. However, it is possible that mechanisms affected by a decrease in muscle pH (enzyme activity, $Ca^{++}$ availability, and membrane permeability) are not yet restored even though lactate and $H^+$ concentrations are normal. Unfortunately, research examining concurrent training has not included such measurements. Further research regarding these mechanisms during concurrent training is needed.

## Centrally Mediated Muscular Fatigue during Strength Training

It is suggested that muscular fatigue may also result from centrally mediated components (Green, 1990; Kent Braun, 1999). These include, but are not exclusive to, supraspinal failure, depression of motor neuron excitability, and presynaptic failure (Green, 1990). For purposes of this paper, these will collectively be referred to as the central component of muscular fatigue. To understand more about the individual components and their assessment please see reviews by Green (1990) and Vollestad (1997).

It has been shown that the central component plays a role in muscular fatigue during strength training (Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Kroon & Naeije, 1988; Hakkinen, 1993; Kent-Braun, 1999). Hakkinen and colleagues (1988) demonstrated that two strength training sessions in one day (4 hours apart) resulted in depressed integrated electromyographic (IEMG) activity along with decreases in maximal force. Although IEMG decreased during both sessions, pre-exercise levels were lower for the second session, suggesting suppressed neural drive from the first session.

The authors suggested that these decreases in IEMG may be due to the training protocol (1-3 repetitions at 70-100% 1RM) being similar to those used to develop the neural component of strength. This was supported by the findings of Hakkinen (1993). Hakkinen demonstrated that training at maximal intensities using Olympic style lifts, IEMG significantly decreased along with force production. It was suggested that decreased force production was partially due to acute fatigue within the neural component.

Kroon and Naeije (1988) demonstrated that exhaustive exercise of the biceps muscles evoked long lasting impairments in muscle performance coinciding with decreased EMG. A decrease in both maximal voluntary contraction and EMG was apparent up to 25 hours post-exercise. Furthermore, muscle endurance time was significantly reduced at both 4 and 25 hours post exercise. Although recovery of some muscle parameters (glycogen and lactate) would have occurred, the ability of the central component to stimulate the muscle might remain impaired.

Recently, work by Kent-Braun (1999) examined the level of contribution to fatigue from both central and peripheral components. Measuring sustained (4 minutes) maximal force of the ankle dorsiflexors along with neural activation and muscle pH, it was determined that both neural and metabolic factors contribute to fatigue. Statistical analysis estimated that central factors (not including excitation-contraction coupling) contributed approximately 20% of the fatigue experienced. Peripheral factors, primarily muscle pH, accounted for the remaining 80%. This led the author to conclude that during sustained maximal isometric contractions, both central and peripheral factors contribute to muscular fatigue. Under different exercise conditions, the contributions from either may vary.

## Central Mechanisms as a Source of Fatigue during Concurrent Training

It is possible that aerobic training may result in reduced neural drive prior to a subsequent strength training session. This may explain some of the reduced strength performance observed (Abernethy, 1993; Leveritt & Abernethy, 1999; Sale *et al.*, 1990). The research examining either concurrent training or the acute effects of aerobic training on strength performance has not included measurements of central fatigue. This makes it difficult to draw conclusions as to the contribution of neural fatigue to impaired strength performances following aerobic training. Speculation can be drawn from the time needed for recovery of neural drive from strength training, however this would likely not be accurate. Strength and aerobic training have different patterns and levels of muscle fiber recruitment depending on the intensity (Fox, Bowers, & Foss, 1993) and therefore might have different fatiguing patterns. Further research on central fatigue with respect to concurrent training is needed.

## Conclusions

The current research examining concurrent training indicates that improvements in strength may or may not be impaired. This may be due to a decrease in training volume, intensity and/or to a direct interference of the metabolic processes which produce the training effect. The effects of concurrent training may be confounded by the selection of training protocols, sequence of training, and the length and type of recovery periods allotted between aerobic and strength training sessions. Furthermore, strength performance in a single strength training session may be limited by muscular fatigue resulting from inadequate restoration of energetic, neural, and metabolic mechanisms.

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# Appendix B

Informed Consent

# Informed Consent

**Purpose of Study:** To investigate the effects of high intensity aerobic interval training on subsequent performance in strength exercise utilizing different recovery periods.

**Procedures:** You will be asked to perform 6 exercise tests and 3 aerobic interval (INT) training sessions. The first test will be a 1-repetition maximum (1RM) leg press test. Approximately 15 minutes following the 1 RM test you will be asked to perform a second test, an incremental exercise test to determine $VO_2max$ on a cycle ergometer. Both of these tests combined should take between 60 and 75 minutes. Each INT training session will consist of a 5-minute sub-maximal warm-up, five 3-minute work intervals at or near the workload used to obtain $VO_2max$ separated by 3-minute active recovery intervals, and a 5-minute cool down period for a total time of 40 minutes. After each training session you will be asked to perform 4 sets to failure of the leg press exercise using a load equal to 75% of your 1RM for one of three different recovery periods (30 minutes, 8 hours, or 24 hours). During the recovery period you will be asked to sustain from any physical activity. On one occasion you will perform only the 4-set leg press test with no previous INT training session. A minimum of 72 hours will separate any testing or training sessions.

**Risk:** Both high intensity interval training and strength training at the required loads have been associated with muscle soreness. This soreness may last between 24 and 72 hours.

**Consent:** I have read the above and agree to participate in this research project at my own risk. I am nineteen years of age or older and regularly take part in strenuous physical activity at least as intense as these tests. I realize that I may expect a thorough explanation and/or demonstration of any procedures and that I may terminate participation at any time in any or all procedures of my own volition.

Having voluntarily assumed participation and risks thereof in the project, I hereby disclaim and release the University of Victoria, its agents, servants or employees, including all personnel involved in the research project, from any and all liability that might otherwise arise as a result of my participation as a research subject in this study.

**Name:** ______________________________ **Date:**__________________

**Signature:** ______________________________

**Witness:** ______________________________

**Signature:** ______________________________

# Appendix C

## Readiness to Work Scale

## Readiness to Work

On a scale of 1 to 10 how ready are you to perform this strength training session:

**1 = Not Ready at All**

**5 = Moderately Ready**

**10 = Very Ready**

Table C-1.

Raw Scores and Means for All Participants on Readiness to Work Questionnaire Immediately Asked Prior to Strength Training for Each Recovery Condition.

| Participant | Control | 4-hour | 8-hour | 24-hour |
|---|---|---|---|---|
| 1 | 6.0 | 8.0 | 8.5 | 8.0 |
| 2 | 7.5 | 9.0 | 9.0 | 9.0 |
| 3 | 6.0 | 7.5 | 7.0 | 10.0 |
| 4 | 3.0 | 9.0 | 8.0 | 5.0 |
| 5 | 9.0 | 9.0 | 6.0 | 8.0 |
| 6 | 7.0 | 7.0 | 8.0 | 7.0 |
| 7 | 7.0 | 7.0 | 7.0 | 8.0 |
| 8 | 7.0 | 7.0 | 8.0 | 7.0 |
| 9 | 6.0 | 7.0 | 7.0 | 7.0 |
| 10 | 6.0 | 8.0 | 8.0 | 6.5 |
| 11 | 6.0 | 5.0 | 9.0 | 7.0 |
| 12 | 5.0 | 8.0 | 9.0 | 9.0 |
| 13 | 5.0 | 8.0 | 6.0 | 6.0 |
| 14 | 8.0 | 6.0 | 6.0 | 9.0 |
| 15 | 9.0 | 8.0 | 8.0 | 7.0 |
| 16 | 10.0 | 7.0 | 8.0 | 9.0 |
| Mean | 6.7 | 7.5 | 7.7 | 7.7 |
| SD | 1.8 | 1.1 | 1.0 | 1.3 |

# Appendix D

## Raw Data

Table D-1.

Total Repetitions, Means, and Standard Deviations (SD) for All Participants Over 4 Sets of Leg Press for Each Recovery Condition.

| Participant | Control | 4-hour | 8-hour | 24-hour |
|---|---|---|---|---|
| 1 | 53 | 32 | 42 | 60 |
| 2 | 64 | 49 | 60 | 64 |
| 3 | 35 | 19 | 26 | 32 |
| 4 | 42 | 27 | 38 | 34 |
| 5 | 57 | 40 | 53 | 53 |
| 6 | 41 | 24 | 39 | 45 |
| 7 | 42 | 34 | 33 | 44 |
| 8 | 45 | 21 | 39 | 56 |
| 9 | 42 | 41 | 40 | 42 |
| 10 | 62 | 39 | 48 | 52 |
| 11 | 65 | 68 | 60 | 68 |
| 12 | 27 | 27 | 26 | 28 |
| 13 | 45 | 28 | 52 | 58 |
| 14 | 48 | 39 | 44 | 53 |
| 15 | 50 | 39 | 43 | 47 |
| 16 | 51 | 47 | 56 | 46 |
| Mean | 48 | 36 | 44 | 49 |
| SD | 10 | 12 | 11 | 11 |

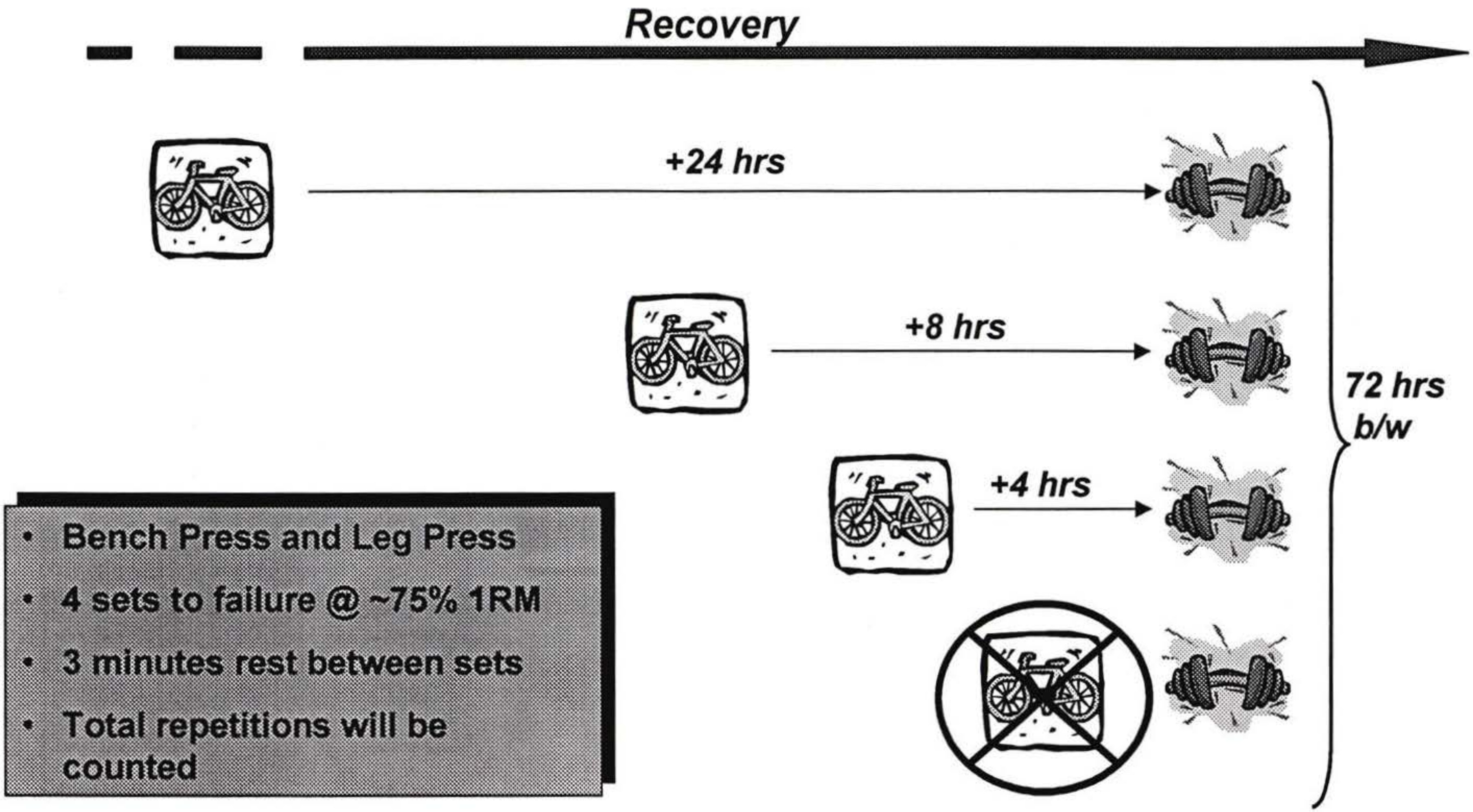
Table D-2.

Total Repetitions, Means, and Standard Deviations (SD) for All Participants Over 4 Sets of Bench Press for Each Recovery Condition.

| Participant | Control | 4-hour | 8-hour | 24-hour |
|---|---|---|---|---|
| 1 | 33 | 33 | 30 | 33 |
| 2 | 28 | 30 | 28 | 29 |
| 3 | 31 | 29 | 33 | 37 |
| 4 | 24 | 26 | 29 | 27 |
| 5 | 37 | 34 | 36 | 34 |
| 6 | 41 | 43 | 38 | 39 |
| 7 | 31 | 30 | 31 | 31 |
| 8 | 36 | 36 | 32 | 32 |
| 9 | 28 | 24 | 27 | 30 |
| 10 | 30 | 33 | 31 | 33 |
| 11 | 32 | 29 | 33 | 30 |
| 12 | 34 | 33 | 34 | 34 |
| 13 | 34 | 33 | 34 | 36 |
| 14 | 30 | 33 | 30 | 28 |
| 15 | 36 | 37 | 40 | 37 |
| 16 | 25 | 28 | 26 | 25 |
| Mean | 32 | 32 | 32 | 32 |
| SD | 4 | 5 | 4 | 4 |

# Appendix E

## Study Design



- Bench Press and Leg Press
- 4 sets to failure @ ~75% 1RM
- 3 minutes rest between sets
- Total repetitions will be counted

Figure E1. Study design layout

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**The Effects of Aerobic Exercise on Strength Performance Under Varying Durations of Recovery**

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January 29, 2001