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PHYSIOLOGICAL ADAPTATIONS OF OARSMEN TO ENDURANCE AND RESISTANCE TRAINING PERFORMED SEQUENTIALLY OR CONCURRENTLY

BY

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A THESIS

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DEDICATION

This thesis is dedicated to my wife, Tracey who provided me with much support and to my daughter, Lauren who made it more worthwhile.

ABSTRACT

The purpose of this research project was to investigate the physiological adaptations to sequential and concurrent endurance and velocity-controlled, circuit resistance training.

Sequencing of high velocity circuit resistance training (HVR) prior to endurance training (group SE) showed a significant progressive increase in maximal oxygen consumption ($\dot{V}O_2max$) and a significant decrease in submaximal exercise responses after endurance training. Significant increases in knee extension and flexion peak torque (PT) were observed in group SE after HVR training. The opposite sequence (group ES) showed improvements in both $\dot{V}O_2max$ and submaximal exercise responses after endurance training. However, the adaptations to HVR training in group ES were somewhat reduced. Also, submaximal exercise responses returned to pre-training levels in group ES after subsequent HVR training ($p < 0.05$). These findings suggested that performing HVR training prior to endurance training may be the preferred sequence.

Sequencing of low velocity circuit resistance training (LVR) and endurance training produced anticipated improvements in strength, cross sectional area (CSA) of quadriceps femoris and aerobic endurance measures regardless of the sequence followed. The sequence of LVR prior to endurance training resulted in no significant decreases in

knee extension PT or total work (TW) despite a significant decrease in CSA after subsequent endurance training. However, $\dot{V}O_2max$ and submaximal exercise responses returned to pre-training levels ($p < 0.05$) after subsequent LVR training in the opposite training group (ES). These findings suggested that conducting LVR training prior to endurance training was preferred as strength was easier to maintain than endurance.

Concurrent endurance and LVR training revealed significant increases in PT, TW and CSA of the knee extensors after 6 and 9 weeks of training but no further increases were observed between 9 and 12 weeks. A significant increase in $\dot{V}O_2max$ occurred after 3 and 6 weeks of training only. However, submaximal $\dot{V}O_2$, HR and BLa showed progressive decreases with significance noted after 3 weeks of training and between 9 and 12 weeks of training. These findings support the notion that the adaptations to resistance training may be compromised by performing endurance training at the same time.

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Chapter 1

INTRODUCTION

Training programs for athletes are often partitioned into pre-season, in-season and off-season phases. Off-season training for sports such as rowing requires the development of both muscular strength and aerobic endurance as the nature of this event demands a high degree of both components (Secher, 1980; Hagerman & Staron, 1983; de Koning et al., 1984; Mahler et al., 1985). Studies describing the physiological characteristics of rowers at various times of the year have shown these athletes to attain a high maximal oxygen consumption and exhibit a great deal of muscular strength (Larsson & Forsberg, 1980; Hagerman & Staron, 1983; Secher, 1983; Clarkson et al., 1984). It is important to the athlete that their endurance training and resistance training programs be organized in such a way that optimal physiological adaptations to both types of training are acheived.

Endurance training enhances the cardiorespiratory system and the oxidative capacity of muscle (Saltin & Rowell, 1980; Holloszy & Coyle, 1984) with little or no effect on muscle strength (Hickson, 1980, Hunter et al., 1987). Resistance training enhances the ability of muscle to develop force and has little or no effect on maximal oxygen consumption

(Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1987). There is some research that found a significant increase in maximal oxygen consumption after circuit training with weights (Stone et al., 1983) or with high velocity resistance exercise (Petersen et al., 1988). Also, Rosler et al (1986) have shown increases in knee extension peak torque at an angular velocity which was similar to the estimated angular velocity used during endurance training on a cycle ergometer. However, it has been suggested that training to improve muscular strength and aerobic endurance may be antagonistic to one another (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1987).

Hickson (1980) has shown that simultaneous endurance training and resistance training may hinder the acquisition of strength but does not diminish adaptations in maximal oxygen consumption. Other research has shown that peak torque at fast angular velocities, but not slow angular velocities, was compromised after concurrent endurance training and high velocity resistance training (Dudley & Djamil, 1985). Hunter et al. (1987) also found that simultaneously training for endurance and strength resulted in some reduction in strength development during the latter weeks of a twelve week training program. Other studies do not support the existence of an interference effect. These studies have shown either a compromise in endurance gains but not strength (Nelson et al., 1984) or similar increases in both strength and endurance after concurrent single leg training compared to resistance training only (Sale, 1986; see also abstracts of the same research project by MacDougall et al., 1987; Jacobs et al., 1987).

Dudley and Fleck (1987) speculated that the lack of optimal strength development when endurance training was performed at the same time may be because of increases in the composition of slow twitch motor units with concomitant decreases in the composition of fast twitch motor units would compromise the capability for strength development. Another suggestion was that a greater total volume of training was acheived with concurrent training which may result in overtraining or a large amount of residual fatigue. Also, untrained subjects were used in previous research which performed concurrent endurance and resistance training (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1987). The response of an athletic population who are accustomed to training for endurance and strength has not been investigated.

Hypertrophied skeletal muscle (compensatory) of the rat induced by surgical removal of a synergist muscle has shown adaptations to endurance training which are similar to nonhypertrophied muscle (Baldwin et al., 1977; Reidy et al., 1985). In contrast, Hunter et al. (1987) showed that previously endurance trained subjects exhibited strength gains after high resistance training while maintaining their current aerobic training. These strength improvements were as great or greater than an untrained group of subjects who followed the same resistance training program. Thus, the suggested incompatibility of simultaneous training for improvements in both strength and endurance may be avoided by a sequential training program which focusses on resistance training prior to endurance training or vice versa.

The type of endurance training and resistance training program may be an important consideration when designing an off-season training program. Endurance training can be performed using either continuous or interval exercise but the physiological adaptations may differ somewhat between these two types of training (Fox et al., 1977; Smith & Wenger, 1981; MacDougall & Sale, 1981; Poole & Gaesser, 1985). During the rowing off-season, the type of endurance exercise typically performed is continuous, moderate intensity training which is designed to enhance the capacity of the aerobic system to perform work. This is done in an attempt to establish an aerobic base in preparation for higher intensity interval training usually conducted during the pre-season.

The majority of resistance training programs have utilized free weights (or Universal and Nautilus equipment) which involves concentric/eccentric muscular contractions. More recently, velocity controlled resistance training has been used to promote strength changes and this type of exercise allows for the generation of a maximal concentric muscular contraction against a controlled velocity (isokinetic) throughout the total range of limb movement in both directions (Hislop & Perrine, 1967; Watkins & Harris, 1983). The advantages to this type of training are reduced muscle soreness probably due to the absence of an eccentric muscle contraction, enhanced safety and reduced chance of injury due to the absence of an external load placed on the individual. Also, velocity controlled resistance training can simulate the velocity, force and type of contraction involved in movement patterns found in various sports. This is an important consideration when designing resistance training programs (Sale & MacDougall, 1981; Gonyea & Sale, 1982).

Thus, endurance and resistance training may be performed in a sequence or concurrently. Sequential training has received little attention in the sport science literature and concurrent training for strength and endurance has shown some controversy. It may be that an optimal combination of training for both during the same training phase may exist. Furthermore, the adaptations to sequential or concurrent training for endurance and resistance training using different velocities of muscular contractions with highly motivated athletes has not been investigated.

Statement of the Purpose

This thesis is written in a paper format and involves three research projects conducted during the 1987, 1988 and 1989 rowing off-seasons. These research projects were designed to investigate the physiological adaptations of endurance training and different velocities of resistance training organized in separate sequential training programs or during a simultaneous training program. The general purpose of each study is provided below.

Study 1: Physiological Adaptations to Endurance and High Velocity Resistance Training Performed in a Sequence

Purpose:

1). To determine the effect of the same endurance and high velocity resistance training programs performed in two different sequences on the following variables:

- knee extension and flexion peak torque at various angular velocities.
- maximal oxygen consumption, submaximal heart rate and submaximal blood lactate levels.

Study 2: Physiological Adaptations to Endurance and Low Velocity Resistance Training Performed in a Sequence

Purpose:

1). To determine the effect of the same endurance and low velocity resistance training programs performed in two different sequences on the following variables:

- **knee extension peak torque and total work at various angular velocities.**
- **cross sectional area of the quadriceps femoris muscle using computer tomography scanning.**
- **maximal oxygen consumption, submaximal heart rate and submaximal blood lactate levels.**

Study 3: Physiological Adaptations to Concurrent Endurance and Low Velocity Resistance Training

Purpose:

1). To determine the effect of conducting simultaneous endurance training and low velocity resistance training on the following variables:

- knee extension peak torque and total work at 1.05 rad · s^{-1}.
- cross sectional area of the quadriceps femoris muscle using computer tomography scanning.
- maximal oxygen consumption and submaximal heart rate, blood lactate and metabolic responses.

Definitions

1). Endurance - the ability to perform prolonged, dynamic muscular work at an exercise intensity which uses energy supplied predominately by the aerobic system and is dependent on the transport and utilization of oxygen.

2). Strength - the maximal force or tension a muscle or muscle group can exert against a resistance during a maximal voluntary contraction at a specified velocity.

3). Velocity Controlled Resistance Training - training at a specified velocity of limb movement against a partial accommodating resistance to improve strength.

4). Endurance training - training at a specified intensity, frequency and duration to improve both the central cardiorespiratory and peripheral muscle components associated with the aerobic system.

References

Baldwin, K., Cheadle, W., Martinez, O., Cooke, D. (1977). Effect of functional overload on enzyme levels in different types of skeletal muscle. Journal of Applied Physiology, 42, 312-317.

Caiozzo, V., Perrine, J. & Edgerton, V. (1981). Training-induced alterations of the in vivo force-velocity relationship of human muscle. Journal of Applied Physiology, 51(3), 750-754.

Coyle, E., Feiring, D., Rotkis, T., Cote, R., Roby, F., Lee, W. & Wilmore, J. (1981). Specificity of power improvements through slow and fast isokinetic training. Journal of Physiology, 51(6), 1437-1442.

Clarkson, P., Graves, J., Melchionda, A., Johnson, J. (1984). Isokinetic strength and endurance and muscle fiber type of elite oarswomen. Canadian Journal of Applied Sport Sciences, 9(3), 127-132.

de Koning, F., Vos, J., Binkhorst, R. & Vissers, A. (1984). Influence of training on the force-velocity relationship of the arm flexors of active sportsmen. International Journal of Sports Medicine, 5, 43-46.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Fox, E., Bartels, R., Klinzing, J. & Ragg, K. (1977). Metabolic responses to interval training programs of high and low power output. Medicine and Science in Sports, 9(3), 191-196.

Gonyea, W. & Sale, D. (1982). Physiology of weight-lifting exercise. Archives of Physical Medicine and Rehabilitation, 63, 235-237.

Hagerman, F. & Staron, R. (1983). Seasonal variations amoung physiological variables in elite oarsmen. Canadian Journal of Sport Sciences, 8(3), 143-148.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Hislop, H. & Perrine, J. (1967). The isokinetic concept of exercise. Physical Therapy, 47, 114-117.

Holloszy, J. & Coyle, E. (1984). Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. Journal of Applied Physiology, 56(4), 831-838.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Jacobs, I., Sale, D. & MacDougall, J. (1987). Combined strength and endurance training effects on muscle enzymatic and histochemical characteristics. (Abstract). Medicine and Science in Sports and Exercise, 19(2), S88.

Kanehisa, H. & Miyashita M. (1983). Specificity of velocity in strength training. European Journal of Applied Physiology, 52, 104-106.

MacDougall, J. & Sale, D. (1981). Continuous vs. interval training: A review for the athlete and the coach. Canadian Journal of Applied Sport Sciences, 6(2), 93-97.

MacDougall, J., Sale, D., Jacobs, I., Garner, S, Moroz, D. 6 Dittmer, D. (1987). Concurrent strength and endurance training do not impede gains in $\dot{V}O_2$max. (Abstract). Medicine and Science in Sports and Exercise, 19(2), S87.

MacDougall, J., Sale, D., Moroz, J., Elder, G., Sutton, J. & Howald, H. (1979). Mitochdrial volume density in human skeletal muscle following heavy resistance training. Medicine and Science in Sports, 11, 164-166.

Mahler, D., Parker, H. & Andresen, D. (1985). Physiologic changes in rowing performance associated with training in collegiate women rowers. International Journal of Sports Medicine, 6(4), 229-233.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance, (Abstract), Medicine and Science in Sports, 16, 184.

Petersen, S., Miller, G., Quinney, H. A. & Wenger, H. (1988). The influence of high-velocity resistance circuit training on aerobic power. Journal of Orthopaedic and Sports Physical Therapy, 9(10). 339-344.

Poole, D. & Gaesser, G. (1985). Response of ventilatory and lactate thresholds to continuous and interval training. Journal of Applied Physiology, 58(4), 1115-1121.

Riedy, M., Moore, R. & Gollnick, F. (1985). Adaptive response of hypertrophied muscle to endur ce training. Journal of Applied Physiology, 59(1), 127-131.

Rosler, K., Conlee, K., Howald, H., Gerber, C. and Hoppeler, H. (1986). Specificity in leg power changes to velocities used in bicycle endurance training. Journal of Applied Physiology, 61(6), 30-36.

Sale, D. (1986). Interaction between concurrent strength and endurance training. (Report Contract No. 8SE85-00082). Downsview, Ontario: Defence and Civil Institute of Environmental Medicine.

Sale, D. & MacDougall, J. (1981). Specificity in strength training: A review for the coach and athlete. Canadian Journal of Applied Sport Sciences, 6, 87-92.

Saltin, B. & Rowell, L. (1989). Functional adaptations to physical activity and inactivity. Federation Proceedings, 39, 1506-1513.

Secher, N. (1983). The physiology of rowing. Journal of Sport Sciences, 1, 23-63.

Smith, D. & Wenger, H. A. (1981). The 10 day aerobic mini-cycle: The effects of interval or continuous training at two different intensities. The Journal of Sports Medicine and Physical Fitness, 21(4), 390-394.

Stone, M., Wilson, G., Blessing, D. and Rozenek, R. (1983). Cardiovascular responses to short-term olympic style weight-training in young men. American Journal of Applied Sport Sciences, 8(3), 134-139.

Watkins, M. & Harris, B. (1983). Evaluation of isokinetic muscle performance. Clinics in Sports Medicine, 2(1), 37-53.

Chapter 2

PAPER 1: PHYSIOLOGICAL ADAPTATIONS TO ENDURANCE AND HIGH VELOCITY RESISTANCE TRAINING PERFORMED IN A SEQUENCE[1]

Introduction

Training programs for many athletes such as rowers, typically focus on the development of muscular strength and aerobic endurance (Hagerman & Staron, 1983; Secher, 1983; Mahler et al., 1985). Resistance training is specifically designed to increase the ability of muscle to generate force and has little or no effect on endurance (Hickson, 1980; Sale & MacDougall, 1981; Stone et al., 1983). However, there is some research that found an increase in maximal oxygen consumption with circuit weight training (Stone et al., 1983) and high velocity resistance training (Petersen et al., 1988). Endurance training enhances the cardiorespiratory system and oxidative enzymes of skeletal muscle but has little effect on strength (Hickson, 1980; Holloszy & Coyle, 1984).

Sale and MacDougall (1981) have suggested that some sport movements may be more specifically trained using velocity specific resistance exercise. Velocity controlled

1. A version of this chapter has been published. Bell, G., Petersen, S., Quinney, H. A. & Wenger, H. A. (1988). Sequencing of endurance and high velocity strength training. Canadian Journal of Sport Sciences, 13(4), 214-219.

resistance training has shown gains in peak torque which are specific to the training velocity (Caiozzo et al., 1981; Kanehisa & Miyashita, 1983; Petersen et al., 1984). Adaptations in the cardiorespiratory system as well as in the peripheral muscle tissue with endurance training are well documented (Holloszy & Coyle, 1984). These adaptations can be partially reflected by a lower heart rate and blood lactate response to submaximal exercise and improvements in maximal aerobic power (Hurley et al., 1984a; Hardman et al., 1986).

The majority of research suggests that endurance training and resistance training performed concurrently by untrained subjects interferes with the acquisition of muscular strength but does not adversely effect the development of maximal oxygen consumption (Hickson, 1980; Dudley & Djamil, 1985; Dudley & Fleck, 1987; Hunter et al., 1987). Other researchers observed minimal differences between groups that conducted endurance and resistance training alone or simultaneously (Nelson, 1984; Sale, 1986). Furthermore, Riedy et al. (1985) and Baldwin et al., (1977) have shown that compensatory hypertrophied skeletal muscle of the rat responds to endurance training in a similar manner to that of untrained muscle. On the other hand, endurance trained individuals showed increases in strength that were similar to untrained individuals while conducting endurance maintenance training (Hunter et al., 1987). Thus, any incompatibility of training to improve muscular strength and aerobic endurance at the same time could be avoided by conducting endurance training and resistance training in separate but sequential programs which focus on resistance training prior to endurance training or vice versa.

Therefore, the purpose of this study was to investigate the effects of the same endurance training and high velocity, circuit resistance training programs performed in two different sequences. Measurements selected to evaluate endurance were submaximal heart rate and blood lactate response to exercise and maximal oxygen consumption. Isokinetic strength was assessed as peak torque throughout a range of angular velocities.

Methods

Subjects and Experimental Design

Sixteen male varsity oarsmen signed informed consent and agreed to participate in two consecutive five week training programs. The mean (± SD) age, height and weight was 22 ± 3.2 years, 182.4 (± 8.3) cm and 78.4 (± 9.6) kg, respectively. Two groups were ranked and matched on knee extension peak torque at 3.14 rad $\cdot$ s^{-1} and absolute $\dot{V}O_2max$ and randomly assigned to the following training groups: group ES trained for endurance first and strength second whereas the opposite sequence was followed by group SE. Testing was conducted before training (Pre), after the initial 5 week training program (Post 1) and after the second 5 week training session (Post 2). A control group (group C) consisting of 8 oarsmen (mean ± SD age, height and weight was [illegible] ± [illegible].9 years, 179.6 ± 10.1 cm and 82.3 ± 9.1 kg, respectively) was tested over a five week period prior to training. This group was allowed to maintain endurance twice a week and strength once a week without an increase in intensity or duration of training. One subject failed to complete the endurance training program of group SE due to illness and his results have been excluded resulting in a sample size of 7 for group SE and a slightly lower initial maximal oxygen consumption of this group. All subjects were asked to refrain from any other training while participating in this study.

Testing Procedures

All rowing performance tests were conducted on a Gjessing Ergorow ergometer designed to simulate rowing exercise. All subjects were asked to refrain from any formal physical activity one day prior to testing.

The subjects reported to the laboratory on Day 1 for an orientation and completed a 10 minute submaximal test consisting of continuous rowing exercise at a resistance of 2 kp with a stroke rate eliciting 600 revs · min^{-1} (196 W). Stroke rates were recorded and maintained during subsequent testing sessions for each subject. Heart rate was recorded during the last 15 s of every minute from a PE 3000 Sport

Tester heart rate monitor (Polar Electric KY) and flywheel revolutions were recorded from an electronic counter. Reliability and validity of Sport Tester heart rate monitors has previously been established (Leger & Thivierge, 1988). Submaximal oxygen consumption was not measured during the submaximal rowing test. A small sample (1 ml) of venous blood was collected from an antecubital vein at rest and one minute after the 10 minute submaximal test. One half of a milliliter was deproteinized in 4% perchloric acid (2 ml), centrifuged for 10 minutes and the supernatant drawn off and stored at -80 degrees Celcius for later determination of lactate concentration (Sigma Chemical Co. Kit 826-UV, 1981). Resting blood lactate and hematocrit remained unchanged during training. Pilot work showed a steady state heart rate to occur using this submaximal protocol and no significant differences were observed between 1 minute (5.7 mmol $\cdot$ l^{-1}) and 5 minute (5.6 mmol $\cdot$ l^{-1}) post exercise blood lactate levels.

On Day 2 right knee extension and flexion peak torque without gravity compensation was determined on a Cybex II isokinetic dynamometer (Lumex Inc., damping setting of 2) and maximal oxygen consumption ($\dot{V}O_2max$) were assessed. The isokinetic dynamometer was calibrated before each test using procedures outlined by the manufacturers. Subjects were seated, secured with a strap at the waist and requested to keep the shoulders against the back rest in an attempt to isolate the knee extensors and flexors. The input axis of the dynamometer was visually aligned with the rotational axis of the knee and the lever arm was secured to the lower tibia just proximal to the medial malleolus. Subjects were instructed to exert a maximal effort through a full range of motion for both extension and flexion of the knee joint. The test began with the knee in the flexed position. Peak torque was determined as the highest point on the torque vs joint angle curve from four maximal continuous repetitions at 2.61, 3.14, 3.66 and 4.19 rad $\cdot$ s^{-1}. The number of repetitions were decreased to three at 0.52, 1.05, 1.57 and 2.09 rad $\cdot$ s^{-1} to reduce test fatigue at the slower angular velocities. Adequate rest (approximately 2 minutes) was provided between each set of exercises. Verbal encouragement was consistently provided by the supervisors.

Maximal oxygen consumption ($\dot{V}O_2max$) was determined during an incremental test on the Gjessing ergometer. Resistance was increased by 2.5 N every minute for seven minutes while stroke rate was maintained at a rate which elicited 500 flywheel revolutions per minute (25 W per minute). During the final two workloads, the resistance was also increased by 2.5 N, but the subjects were required to increase stroke rate to a maximum. The subjects were encouraged to continue beyond the ninth minute at a maximal stroke rate if able. However, no subject was able to continue past ten minutes. The main criterion for attainment of $\dot{V}O_2max$ were a peak and/or plateau in $\dot{V}O_2$ with an increase in power output, and secondarily, a respiratory exchange ratio of greater than 1.15, age-predicted or known maximum heart rate and/or volitional exhaustion (Thoden et al., 1982). Expiratory gases were collected and analyzed every 30 seconds via a Beckman Metabolic Measurement Cart. Calibration was conducted immediately before and after each test with gases of known concentration. Heart rate was recorded during the last 15 seconds of each minute of exercise from a Sport Tester heart rate monitor.

Training Program

The endurance program consisted of training five days a week for 5 weeks on Concept II rowing ergometers at an intensity of 85 to 90% of maximum heart rate determined during the $\dot{V}O_2max$ test (approximately 75% of $\dot{V}O_2max$). Subjects exercised for 40 minutes a session and progressively increased the duration by 5 minutes per week until 60 minutes of continuous rowing was achieved. Training intensity was monitored by each subject every session with Sport Tester heart rate monitors. Responses to exercise performed on the Concept II ergometer has been shown to be similar to the Gjessing ergometer and to actual sculling (Chenier & Leger, 1986).

High velocity, circuit resistance (HVR) training was conducted on variable resistance hydraulic equipment (Hydra-Fitness Industries) 4 times a week for 5 weeks.

Twelve equipment stations were used to exercise upper and lower body muscle groups involved in rowing and were completed in the following order: 1). unilateral seated knee extension and flexion; 2). standing bilateral elbow flexion and extension with shoulder abduction and adduction; 3). bilateral seated hip and knee extension; 4). supine bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 5). seated bilateral elbow flexion and extension with shoulder abduction and adduction and bilateral seated hip and knee extension and flexion; 6). unilateral reclined hip abduction and adduction; 7). supine bilateral horizontal shoulder abduction and adduction; 8). unilateral supine hip flexion and extension; 9). unilateral seated elbow flexion and extension; 10). unilateral seated knee extension and flexion; 11). seated bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 12). bilateral seated hip and knee extension. Situps were also included as an extra station.

Training was conducted in a circuit consisting of two intervals of 20 seconds exercise: 20 seconds rest with 60 seconds between stations (Petersen et al., 1984; 1988) with upper and lower body stations alternated. The hydraulic cylinders do not provide a true isokinetic loading system. However, average angular velocity may be calculated from the range of motion and the number of repetitions performed in a fixed time period. On average, 20 repetitions of knee extension and flexion were required in 20 seconds of exercise throughout a 180 degree range of motion. Each session was monitored by a supervisor who adjusted the cylinders to maintain consistent angular velocities of approximately 3.0 rad · s^{-1}. Depending on the equipment station and range of motion, angular velocity of training was approximated for all stations. The resistance settings were increased when the number of repetitions consistently exceeded 20 on two consective training sessions. The subjects progressively increased from 2 to 3 complete circuits by the end of the second week with 4 minute rest between circuits. Number of repetitions and resistance settings were recorded by the subjects each session.

Statistical Analysis

Two separate 3 x 2 ANOVA with repeated measures were used to compare both the 5 week endurance training programs and the 5 week strength training programs of group ES and group SE to the 5 week control group on the following variables: peak torque at 8 different angular velocities, maximal oxygen consumption, submaximal heart rate and submaximal blood lactate levels. The pre-training (Pre), following 5 weeks of training (Post 1) and following 10 weeks of training (Post 2) dependent measures for groups ES and SE were analysed with a 2 x 3 ANOVA with repeated measures. Any significant differences observed between groups prior to training were analysed with an analysis of covariance using the pretest as the covariate. Multiple comparisons were conducted with a Duncan post hoc analysis. The alpha level was set a priori at $p < .05$.

Results

A significant group (ES and SE) by time (Pre, Post 1 and Post 2) interaction was found for submaximal heart rate (HR), blood lactate (BLa) and $\dot{V}O_2max$. Table 2.1 shows that submaximal HR and BLa levels were decreased in both groups ES and SE after endurance training only ($p < .05$). Also, submaximal HR significantly increased to pre-training levels after HVR in group ES. The control group exhibited no significant change in submaximal HR or BLa.

Table 2.2 shows that absolute and relative $\dot{V}O_2max$ increased with endurance training in both groups regardless of the sequence of training. Group SE exhibited a significant progressive increase in both absolute and relative $\dot{V}O_2max$ from pre-training to after 5 and 10 weeks of training. Relative $\dot{V}O_2max$ was significantly higher for group ES compared to group SE prior to training and after 5 weeks of training (post 1). The results of the ANCOVA analysis support the results of the ANOVA for relative $\dot{V}O_2max$ changes reported in Table 2.2. Both relative and absolute $\dot{V}O_2max$ for the control group remained unchanged and relative $\dot{V}O_2max$ was significantly lower than group ES on post 1 and group SE on post 2. Absolute $\dot{V}O_2max$ was significantly lower after the control period compared to after endurance training (post 2) in group SE. No change in body weight occurred in either group during training.

No significant group or interaction effects were found for peak torque but a significant main effect due to training was observed. Peak torque for right knee extension was significantly increased in group SE at 3.66 rad $\cdot$ s^{-1} and at 4.19 rad $\cdot$ s^{-1} after 5 weeks of HVR training (Figure 2.1). Group ES observed a significant increase in knee extension peak torque at 0.52 rad $\cdot$ s^{-1} after both the endurance and HVR training programs (Figure 2.2).

Peak torque for right knee flexion was significantly improved at 1.57, 2.61, 3.14, 3.66 and 4.19 rad $\cdot$ s^{-1} after HVR training in group SE (Figure 2.3). Significant knee flexion improvements for group ES with 5 weeks of HVR training occurred at 3.66 and 4.19 rad $\cdot$ s^{-1} only (Figure 2.4). Furthermore, significant increases in peak torque at 1.57, 2.61, 3.14, 3.66 and 4.19 rad $\cdot$ s^{-1} were observed in group ES after ten weeks of training. A significant increase in peak torque at 2.61 rad $\cdot$ s^{-1} was observed in group ES with endurance training on the rowing ergometer.

The control group exhibited a significant decrease in peak knee extension torque at 0.52 rad $\cdot$ s^{-1} while no knee flexion changes were observed during the 5 week control period.

Discussion

The present study investigated the physiological adaptations to endurance and high velocity, circuit resistance (HVR) training performed in two different sequences. This research was conducted during the rowing off-season in a sample consisting of oarsmen. These athletes typically perform some form of endurance and resistance training during this phase of their annual training calendar. The endurance program was of moderate intensity (75% $\dot{V}O_2max$) with duration progressively increased to primarily enhance submaximal response to exercise and to improve maximal oxygen consumption. The circuit resistance program involved training at a relatively high velocity to emphasize torque expression at fast angular velocities.

Heart rate and blood lactate response to submaximal exercise was decreased and $\dot{V}O_2max$ was increased with endurance training but submaximal exercise responses were not significantly altered with HVR training. The changes observed after endurance training were similar in magnitude regardless of the sequence of training followed by either experimental group. The decrease in heart rate to a fixed workload after endurance training may be due in part to an improvement in stroke volume output, an improvement in mechanical efficiency, a decrease in the sympathetic/ parasympathetic ratio, and a decrease in catecholamine response to exercise (Clausen, 1977; Henriksson, 1977;

Rowell, 1980; Rosiello et al., 1987). The decrease in submaximal blood lactate level may be partly due to a increase in oxidative capacity of muscle, a decrease in lactate production and an increase in the rate of lactate removal from the blood (Donovan & Brooks, 1983; Holloszy & Coyle, 1984; Hurley et al., 1984a; Hardman et al., 1986; Favier et al., 1986).

Other research has shown that circuit resistance training has some (Stone et al., 1983; Petersen et al. 1988) or no effect on $\dot{V}O_2max$ or hemodynamic responses to submaximal exercise (Gettman et al., 1978; Wilmore et al., 1978; Hurley et al., 1984b). In the present study, HVR training produced an increase in $\dot{V}O_2max$ in group SE but no significant decreases in submaximal exercise responses were observed. Furthermore, the decreases in submaximal heart rate and blood lactate response, that occurred after endurance training in group ES, returned to pre-training levels after subsequent HVR training even though $\dot{V}O_2max$ was maintained. This suggests that HVR training produced an increase in $\dot{V}O_2max$ probably due to an increase in cardiac output. Hardman et al. (1986) observed improvements in submaximal endurance as measured by various cardiorespiratory parameters and blood lactate response to exercise, of over 200% with only modest improvements in $\dot{V}O_2max$. Hurley et al. (1984a) found that intense endurance training lowers blood lactate concentration at the same relative intensity and the trained subjects had to exercise at a higher percentage of $\dot{V}O_2max$ to reach the same lactate levels than was required prior to training. Davies et al. (1981) observed a 400% increase in the endurance capacity of rat skeletal muscle with only a 14% increase in $\dot{V}O_2max$. It is reasonable to conclude that the two types of training performed in this study had a differential effect on $\dot{V}O_2max$ and submaximal exercise responses. However, it may be that rowing exercise is a complex movement pattern and increases in submaximal rowing exercise performance may be specific to the type of training program.

The significant increase in $\dot{V}O_2max$ after high velocity resistance training in group SE was similar in magnitude to that observed after endurance training in either group. This finding could be the result of the lower initial $\dot{V}O_2max$ in group SE prior to training. However, the endurance training program was of moderate intensity and was not specifically designed to maximally stress $\dot{V}O_2max$ whereas the HVR training program involved high intensity intermittent work conducted in a circuit which could influence $\dot{V}O_2max$. Also, the increase in $\dot{V}O_2max$ that occurred after endurance training in group ES was not further increased with subsequent HVR training. It is unlikely that this finding is due to a difference in the training programs as both groups followed the same HVR training programs. The similar improvements observed between group ES and SE for both $\dot{V}O_2max$ and submaximal response to exercise ensure that the endurance training programs were equivalent. Group ES began the HVR training program at a much higher fitness level which maintained but did not improve $\dot{V}O_2max$. Therefore, prior endurance training may have hindered any $\dot{V}O_2max$ benefit that could be attained from the subsequent HVR training program. However, HVR training seemed to provide a sufficient training stimulus to evoke a change in $\dot{V}O_2max$ for group SE without prior endurance development.

The variable resistance hydraulic resistance training equipment utilized in this study provides maximal resistance throughout the full range of motion in both directions of limb movement. The equipment attempted to simulate the movement pattern and type of muscular contraction involved in rowing especially in knee and hip extension/flexion. This specificity in limb movement, mode and velocity of contraction is important for optimizing sport performance (Sale & MacDougall, 1981). High speed isokinetic resistance training has been shown to enhance peak torque at low and high velocity (Coyle et al., 1981; Dudley & Djamil, 1985). However, other research refutes this hypothesis and indicates that the transfer of strength gains from fast velocity resistance training occurs only at the faster angular velocities (Caiozzo et al., 1981; Kanehisa & Miyashita, 1983). The present results support this contention. Furthermore, peak torque improvements seem to be greater and occur at a wider range of angular velocities for knee flexion as compared to knee extension. This may reflect a greater potential for peak torque adaptation in the knee flexors for this subject pool since both the knee extensors and flexors received similar amounts of exercise stimulus in each training session.

The progressive improvement in peak torque which occurred during the course of both the endurance and HVR training programs in group ES for knee flexion and somewhat for knee extension is evidence that endurance exercise on the rowing ergometer may enhance peak torque at fast angular velocities. It may also be that the training velocity of rowing on the ergometer approximated an angular velocity of 3.14 rad $\cdot$ s $^{-1}$. Other research observed specific peak torque improvements near the estimated average knee angular velocity used during cycling after eight weeks of cycle ergometer training (Rosler et al., 1986).

Petersen et al. (1984) have reported that initial $\dot{V}O_2max$ was not a limiting factor to knee extension and flexion peak torque adaptations in previously well-trained subjects. This was not the case for group ES in the present study which had a high initial $\dot{V}O_2max$ due to endurance training prior to HVR training. Thus, group ES was unable to show a significant improvement in peak torque for knee extension with subsequent HVR training suggesting that endurance training may have reduced the training adaptations to HVR training. However, a significant increase in knee flexion after HVR training was observed in group ES. This is in contrast to group SE where peak torque improvements in knee extension and flexion occurred after HVR training when it preceeded endurance training. The reason for this reduced ability to enhance peak torque in the knee extensors when endurance training precedes HVR training is not known. It may be that the adaptation in motor unit recruitment of the leg extensors is similar when rowing on the ergometer and during HVR training. It may also be that the duration, frequency or intensity of training was not sufficient to elicit maximal gains in peak torque when endurance training preceeded HVR training.

In summary, high velocity, circuit resistance and endurance training can influence physiological adaptations to each program depending on the sequence followed. Prior endurance training may impede the development of subsequent fast velocity peak torque gains. The HVR training program maintained $\dot{V}O_2max$ but not the submaximal endurance gains observed after endurance training. The opposite sequence of HVR training prior to endurance resulted in peak torque improvements at fast angular velocities and an increase in $\dot{V}O_2max$. Submaximal response to exercise was enhanced with endurance training only, regardless of the sequence followed. This study seems to indicate that the prior development of aerobic fitness is not a necessary requirement for fast velocity peak torque improvements. Thus, if the goal of the off-season training program was to elicit improvements in peak torque at fast angular velocities, $\dot{V}O_2max$ and submaximal response to exercise immediately prior to the pre-season training program, the sequence of high velocity, circuit resistance training prior to endurance training may be preferred based on the present results.

References

Chenier, D. & Leger, L. (1986). $\dot{V}O_2$ peak with 2 rowing ergometers (Concept II and Gjessing) and a single scull on water. (Abstract). Canadian Journal of Applied Sport Sciences, 8P.

Clausen, J. (1977). Effect of physical training on the cardiovascular adjustments to exercise in man. Physiological Reviews, 57(4), 779-815.

Coyle, E., Feiring, D., Rotkis, T., Cote, R., Roby, F., Lee, W. & Wilmore, J. (1981). Specificity of power improvements through slow and fast isokinetic training. Journal of Applied Physiology, 51(6), 1437-1442.

Davies, K., Packer, L. & Brooks, G. (1981). Biochemical adaptations of mitochondria, muscle, and whole-animal respiration to endurance training. Archives of Biochemistry and Biophysics, 209(2), 539-554.

Dodd, S., Powers, S., Callender, T. & Brooks, E. (1984). Blood lactate disappearance at various intensities of recovery exercise. Journal of Applied Physiology, 57(5), 1462-1465.

Donovan, C. & Brooks, G. (1983). Endurance training affects lactate clearance, not lactate production. Journal of Applied Physiology, 244(7), E83-E92.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Favier, R., Constable, S., Chen, M. & Holloszy, J. (1986). Endurance exercise training reduces lactate production. Journal of Applied Physiology, 61(3), 885-889.

Gettman, L., Ayers, J., Pollock, M. and Jackson, A. (1978). The effect of circuit weight training on strength, cardiovascular function, and body composition of adult men. Medicine and Science in Sports, 10, 171-176.

Hagerman, F. & Staron, R. (1983). Seasonal variations among physiological variables in elite oarsmen. Canadian Journal of Sport Sciences, 8(3), 143-148.

Hardman, A., Williams, C. and Wootton, S. (1986). The influence of short-term oxygen uptake, submaximal endurance and the ability to perform brief, maximal exercise. Journal of Sport Science, 4, 109-116.

Henriksson, J. (1977). Training induced adaptation of skeletal muscle and metabolism during submaximal exercise. Journal of Physiology, 270, 661-675.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Holloszy, J. & Coyle, E. (1984). Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. Journal of Applied Physiology, 56(4), 831-838.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Hurley, B., Hagberg, J., Allen, W., Seals, S., Young, J., Cuddihee, R. & Holloszy, J. (1984a). Effect of training on blood lactate levels during submaximal exercise. Journal of Applied Physiology, 56(5), 1260-1264.

Hurley, B., Seals, D., Ehsani, A., Cartier, L., Dalsky, G., Hagberg, J. and Holloszy, J. (1984b). Effects of high intensity strength training on cardiovascular function. Medicine and Science in Sports and Exercise, 16(5), 483-488.

Kanehisa, H. & Miyashita M. (1983). Specificity of velocity in strength training. European Journal of Applied Physiology, 52, 104-106.

Leger, L. & Thivierge, M. (1988). Heart rate monitors: validity, stability, and functionality. The Physician and Sportsmedicine, 15(5), 143-151.

Mahler, D., Parker, H. & Andresen, D. (1985). Physiologic changes in rowing performance associated with training in collegiate women rowers. International Journal of Sports Medicine, 6(4), 229-233.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance, (Abstract), Medicine and Science in Sports, 16, 184.

Petersen, S., Miller, G., Quinney, H. A. & Wenger, H. (1988). The influence of high-velocity resistance circuit training on aerobic power. Journal of Orthopaedic and Sports Physical Therapy, 9(10). 339-344.

Petersen, S., Miller, G., Wenger, H. & Quinney, H. A. (1984). The acquisition of muscular strength: the influence of training velocity and initial $\dot{V}O2max$. Canadian Journal of Applied Sport Science, 9(4): 176-180.

Riedy, M., Moore, R. & Gollnick, P. (1985). Adaptive response of hypertrophied muscle to endurance training. Journal of Applied Physiology, 59(1), 127-131.

Rosiello, R., Mahler, D. & Ward, J. (1987). Cardiovascular responses to rowing. Medicine and Science in Sports and Exercise, 19(3), 239-245.

Rosler, K., Conley, K., Howald, H., Gerber, C. & Hoppeler, H. (1986). Specificity of leg power changes to velocities used in bicycle endurance training. Journal of Applied Physiology, 61(6), 30-36.

Rowell, L. (1980). What signals govern the cardiovascular responses to exercise? Medicine and Science in Sports and Exercise, 12(5), 307-315.

Sale, D. (1986). Interaction between concurrent strength and endurance training. (Report Contract No. 8SE85-00082). Downsview, Ontario: Defence and Civil Institute of Environmental Medicine.

Sale, D. & MacDougall, J. (1981). Specificity in strength training: A review for the coach and athlete. Canadian Journal of Applied Sport Sciences, 6, 87-92.

Secher, N. (1983). The physiology of rowing. Journal of Sport Sciences, 1, 23-63.

Sigma Chemical Company (1981). The quantitative determination of pyruvic acid and lactic acid. Sigma Technical Bulletin No. 826-UV. Sigma Chemical Company: St. Louis.of Applied Physiology, 44, 17-23.

Thoden, J., Wilson, B. & MacDougall, J. (1982). Testing Aerobic Power. In MacDougall, J., Wenger, H. & Green, H. (Eds), Physiological testing of the elite athlete. Mutual Press Limited: Ottawa.

Stone, M., Wilson, G., Blessing, D. and Rozenek, R. (1983). Cardiovascular responses to short-term olympic style weight-training in young men. American Journal of Applied Sport Sciences, 8(3), 134-139.

Wilmore, J., Parr, R., Girandola, R., Ward, P., Vodak, P., Barstow, J., Pipes, T., Romero, G. and Leslie, P. (1978). Physiological alterations to circuit weight training. Medicine and Science in Sports, 10, 79-84.

Table 2.1 Submaximal heart rate and blood lactate before training (pre), after 5 weeks (post 1) and after 10 weeks (post 2) of training for all groups.

	Heart Rate ($b \cdot min^{-1}$)			Blood Lactate ($mmol \cdot l^{-1}$)		
Group	Pre	Post 1	Post 2	Pre	Post 1	Post 2
ES	173	167[a]	172[b]	5.4	4.1[a]	5.1
	(4.7)	(4.9)	(4.2)	(0.9)	(0.8)	(0.9)
SE	181	179	173[ab]	6.7	6.1	4.9[a]
	(5.1)	(5.1)	(5.8)	(0.8)	(1.2)	(0.8)
Control	178	182		5.9	6.2	
	(5.5)	(3.1)		(0.8)	(0.6)	

a = significantly different from pre-training, $p < 0.05$.

b = significantly different from post 1, $p < 0.05$.

Values are means (SE).

Table 2.2 Absolute and relative $\dot{V}O_{2}max$ for all groups before (pre), after 5 weeks (post 1) and after 10 weeks (10) of training.

	Absolute ($l \cdot min^{-1}$)			Relative ($ml \cdot kg^{-1} \cdot min^{-1}$)		
Group	Pre	Post 1	Post 2	Pre	Post 1	Post 2
ES	4.21	4.45[a]	4.40[a]	54.5	58.1[ac]	57.7[ae]
	(0.14)	(0.14)	(0.14)	(0.9)	(1.3)	(1.1)
SE	4.00	4.27[a]	4.58[abe]	50.1[d]	53.5[ad]	58.3[abe]
	(0.13)	(0.14)	(0.15)	(1.0)	(1.0)	(1.8)
Control	4.10	4.05		53.4	52.3	
	(0.14)	(0.12)		(1.0)	(1.1)	

a = significantly different from pre-training, $p < 0.05$.

b = significantly different from post 1, $p < 0.05$.

c = significantly different from the other groups (post 1), $p < 0.05$.

d = significantly different from group ES, $p < 0.05$.

e = significantly different from control (post 1), $p < 0.05$.

Values are means (SE).

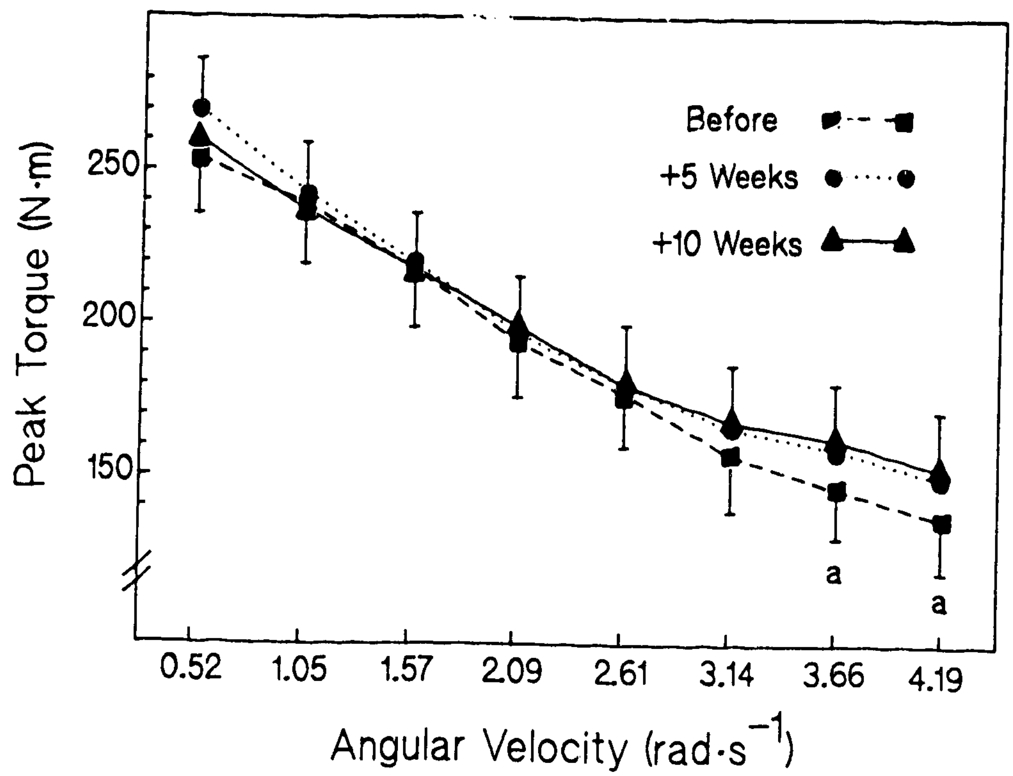

Figure 2.1 Right knee extension peak torque at various angular velocities for group SE before training, after 5 weeks and after 10 weeks of training.

a = significantly different from week 5 and 10, $p < 0.05$. Values are means (SE).

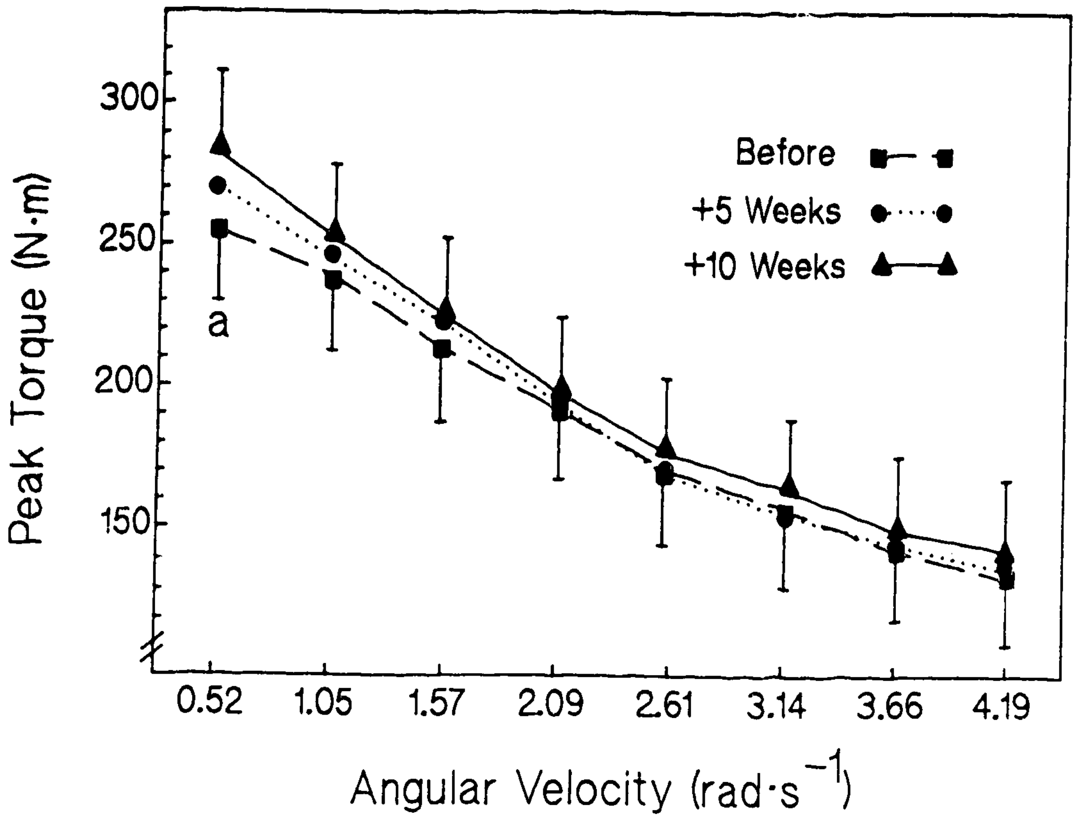

Figure 2.2 Right knee extension peak torque at various angular velocities for group ES before training, after 5 weeks and after 10 weeks of training.

a = significantly different from week 5 and 10, $p < 0.05$. Values are means (SE).

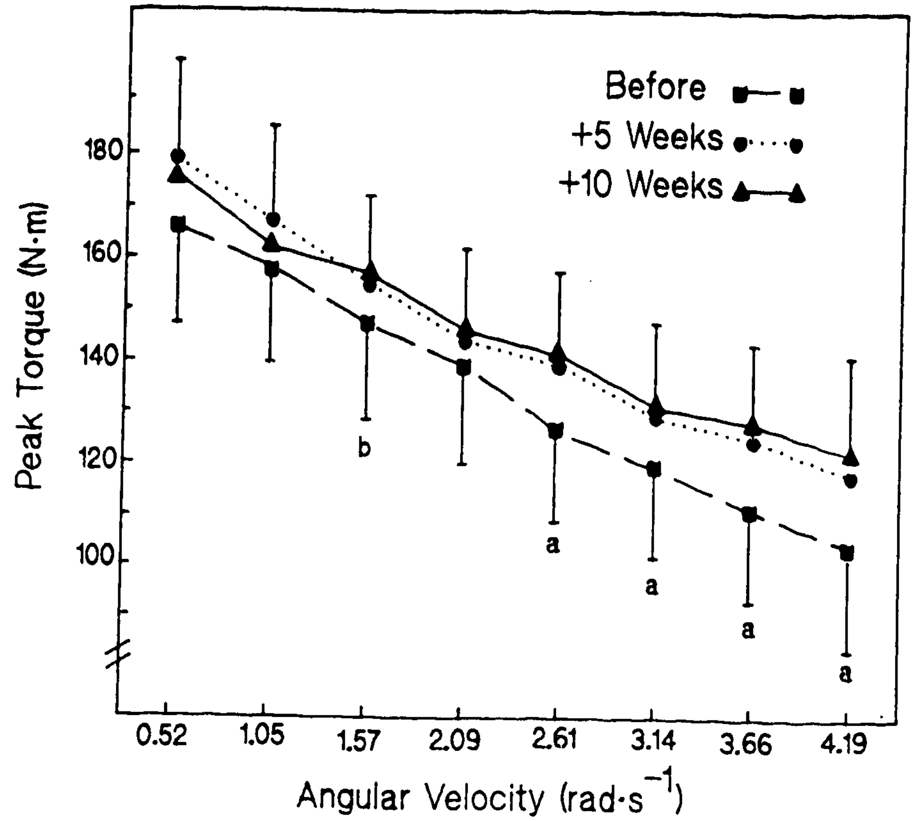

Figure 2.3 Right knee flexion peak torque at various angular velocities for group SE before training, after 5 weeks and after 10 weeks of training.

a = significantly different from week 5 and 10, $p < 0.05$.

b = significantly different from before to after 10 weeks, $p < 0.05$.

Values are means (SE).

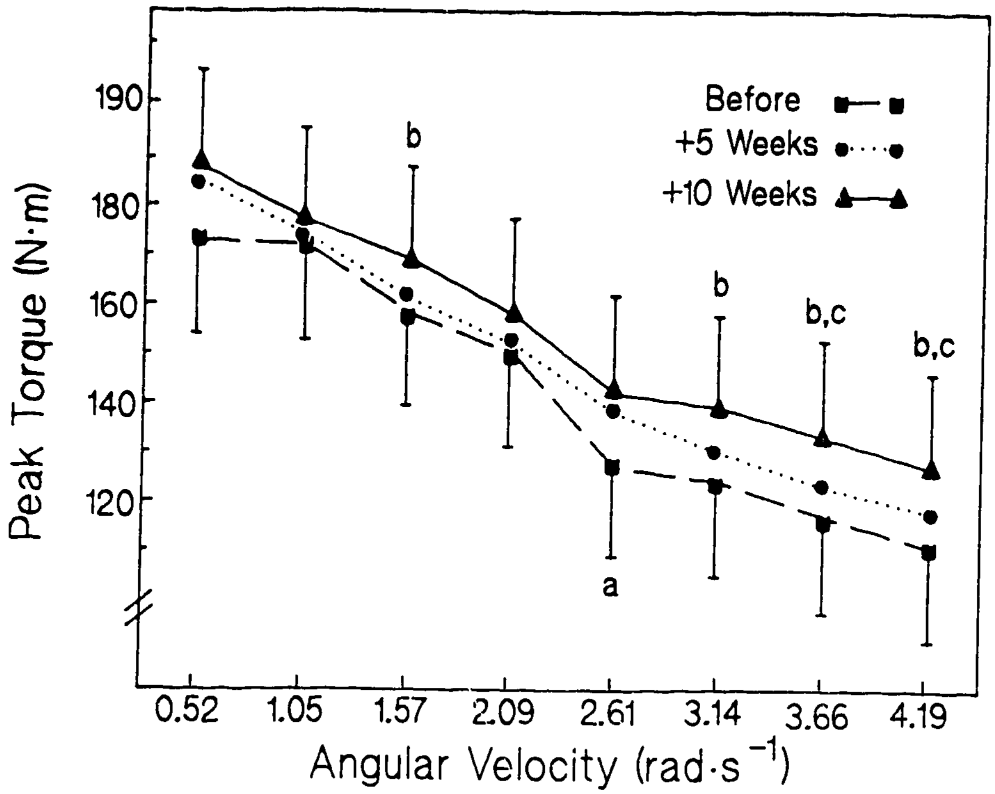

Figure 2.4 Right knee flexion peak torque at various angular velocities for group ES before training, after 5 weeks and after 10 weeks of training.

a = significantly different from week 5 and 10, $p < 0.05$.

b = significantly different from before to after 10 weeks, $p < 0.05$.

c = significantly different from 5 to 10 weeks, $p < 0.05$.

Values are means (SE).

Chapter 3

PAPER 2: PHYSIOLOGICAL ADAPTATIONS TO ENDURANCE AND LOW VELOCITY RESISTANCE TRAINING PERFORMED IN A SEQUENCE[2]

Introduction

The adaptations to endurance training and resistance training, when performed separately, are well founded (Clausen, 1977; Costill, 1979; Holloszy & Coyle, 1984; Luthi et al., 1986). Furthermore, high resistance training has shown little or no effect on endurance (MacDougall et al., 1979; Hickson, 1980; Dudley & Djamil, 1985) and endurance training produces little change in strength (Hickson, 1980; Hurley et al., 1984b; Dudley & Djamil, 1985). Simultaneous resistance and endurance training has produced compromises in strength gains (Hickson, 1980; Dudley & Djamil, 1985; Dudley & Fleck, 1987; Hunter et al., 1987) whereas other research suggests that this interference effect may not be universal (Nelson et al., 1984; Sale, 1986). Resistance and endurance training may also be performed in a sequence, thus avoiding any potential interference effects. Research has shown that the physiological adaptations to high velocity resistance training and endurance training may be somewhat dependent on the sequence of training followed (Bell et al.,

2. A version of this chapter has been submitted for publication. Bell, G., Petersen, S., Quinney, H. A., Wessel, J., Bagnall, K. (1989). Submitted to Medicine and Science in Sports and Exercise.

1988).

This study examined the physiological adaptations of two different sequences of the same low velocity, circuit resistance training and endurance training. Measurements made to indicate endurance capabilities included heart rate and blood lactate responses to submaximal work and maximal oxygen consumption. Measurement of strength included knee extension peak torque and total work. Cross sectional area of quadriceps femoris muscle was also determined.

Methods

Subjects and Experimental Design

The subjects consisted of 20 volunteers who were on the University of Alberta and Edmonton rowing team. The mean (± SD) age, height and weight was 23 ± 4.1 years, 183.3 ± 8.2 cm and 77.5 ± 5.6 kg, respectively. However, three subjects dropped out of the study for reasons not related to the study. Prior to data collection, the subjects were instructed on use of the equipment and given an explanation of all testing and training procedures. The subjects were randomly assigned to two training groups: group ES (n = 8) which performed endurance training before low velocity resistance training or group SE (n = 9) which performed low velocity resistance prior to endurance training. A time-series experimental design was chosen (Campbell & Stanley, 1963) as it is difficult to obtain control data from an equally trained sample of subjects since most athletic populations are required to continue training for their sport.

Control values were obtained on two occasions: 5 weeks prior to the commencement of training and immediately before training. This time interval was used as a control period during which the subjects were asked to maintain their normal fitness level (endurance training twice and resistance training once each week) without an increase in intensity or duration of training. Adherence to these guidelines did not present a problem since the control phase was conducted early in the off-season for these athletes. All subjects were asked to refrain from any other organized training during this period and had two days of complete rest with no training prior to the testing sessions.

Testing Procedures

Heart rate and blood lactate responses to an absolute submaximal workload and maximal oxygen consumption during a test to exhaustion. All tests were performed on an ergometer designed to imitate rowing skills (Gjessing Ergorow, Bergen, Norway). The submaximal rowing test consisted of 10 minutes of rowing exercise while maintaining a power output (PO) of 196 Watts. This workload was accomplished with a resistance setting of 19.6 N and 600 revolutions of the flywheel per minute. The stroke rate required to maintain this power output was determined for each subject with an electronic rate watch during the initial testing session and attempts were made to maintain the same stroke rate during subsequent testing by providing verbal feedback of stroke rate to the subjects every minute. Heart rate was calculated during the last fifteen seconds of each minute of exercise from electrocardiograph (Cambridge, Model VS4) chart recordings and averaged over the last 6 minutes of the submaximal test. Previous work conducted in our laboratory using oarsmen has shown $\dot{V}O_2$ and heart rate to reach steady state within 3 to 4 minutes of exercise using the above protocol. However, oxygen consumption was not assessed during the training program. A small (1 ml) blood sample was taken by venipuncture from an antecubital vein of either arm one minute after rowing exercise ceased. One half of a milliliter of whole blood was deproteinized in 4 % perchloric acid (2 ml) and centrifuged for 10 minutes. The supernatant was drawn off and stored at -80 degrees Celcuis and was later analyzed enzymatically for lactate concentration (Sigma Chemical Co. Kit 826-UV, 1981). No change in resting blood lactate levels or hematocrit was observed during training. The one minute delay was necessary to get the subject into position to draw the blood sample and further pilot work using oarsmen has shown that blood lactate concentration was not significantly different between 1 (5.7) and 5 (5.6) minutes after the 10 minute submaximal test.

Maximal oxygen consumption ($\dot{V}O_2max$) was determined during a continuous, incremental test to exhaustion on the ergometer. Resistance was increased by 2.5 N every minute for seven minutes while stroke rate was maintained at a submaximal rate which elicited 500 flywheel revolutions per minute (25 W per minute). During the final two workloads, the resistance was also increased by 2.5 N. However, the subjects were required to increase stroke rate to a maximum. The subjects were verbally encouraged to continue beyond the ninth minute at a maximum stroke rate if able. However, no subject was able to continue past ten minutes. The main criterion used to establish $\dot{V}O_2max$ was attainment of a peak and/or plateau in $\dot{V}O_2$ with an increase in power output. Further criteria to confirm that $\dot{V}O_2max$ was achieved included: a respiratory exchange ratio > 1.15; age-predicted or known maximum heart rate was reached; and, volitional exhaustion prevented further exercise (Thoden et al., 1982). Expiratory gases were collected and analysed every 30 seconds with a Beckman Metabolic Measurement Cart (MMC). Calibration with known gas concentrations was conducted immediately before and after each test. Heart rate was calculated from electrocardiograph recordings taken during the last 15 s of each minute of the $\dot{V}O_2max$ test.

Strength was determined by measuring the highest single torque value (peak torque) achieved on the torque versus angle curve and total work performed during four maximal knee extensions at four different angular velocities (1.05, 2.09, 3.14 and 4.01 rad · s^{-1}) on a Kinetic Communicator (KinCom) isokinetic dynamometer (gravity compensated). The dynamometer was calibrated before and after the study. The reliability and validity of the KinCom dynamometer (Farrel & Richards, 1986) and a concentric-eccentric test protocol (Wessel et al., 1988) have previously been established. The testing mode of the dynamometer was concentric-concentric for knee extension and flexion. However, only knee extension data was reported for this study as it was emphasized in the training program and knee extensors are a major muscle group used in rowing. A minimum force of 20 N with no pause between contractions was chosen and the range of motion was 95 to 10 degrees from full extension as some subjects were unable to acheive full extension of the knee in the sitting position. Subjects were secured with a strap around the waist at the level of the pelvis and around the upper thigh while in the seated postion and were allowed to grasp the seat during the test. The input axis was visually aligned with the lateral epicondyle of the femur and the lever arm was positioned at the lower right tibia, proximal to the medial malleolus. The right limb was weighed at anatomical neutral position (knee extended) to compensate for gravity. A submaximal warmup was performed at each angular velocity and 1 to 2 minutes rest was permitted after the warmup, prior to each test and between subsequent tests. Maximal effort throughout the whole range of limb movement was requested by the investigators and verbal encouragement was provided to the subjects during all testing sessions.

Cross sectional area (CSA) of the right quadriceps femoris muscle group of each subject was assessed by using computed tomography (CT) scanning (General Electric Medical Systems, Model 9800). The radiographs were taken after abstaining from any formal exercise for one day. A 1 cm wide scan (120 kVp, 100 mA, 3 s) was taken at a point measured midway between the upper crest of the greater trochanter and the knee joint space of the right femur. The anatomical landmarks were determined by the same investigator throughout the study. A scout scan of the femur and knee joint was also taken and the distance from the femoral intercondylar notch to the level of the transverse scan site was determined by computer. Any one scan which was not within the 1 cm boundary when compared to the other scans for the same individual was disregarded. For this reason, the results from 2 subjects in group ES and 3 subjects in group SE were omitted, resulting in only 6 subjects representing each group for the cross sectional area data. Contact prints were made of the radiographs and the quadriceps femoris muscle group was outlined on the photographs prior to computer analysis to enhance the precision of determining the appropriate muscles. CSA of the quadriceps femoris muscle was determined by computer assisted planimetry. Unadjusted inter- and intra-rater reliability coefficients for a single measurement of CSA on 20 different scans was .997 and .998, respectively (interclass correlation coefficients). Also, the intra-rater reliability coefficient was .978 for landmarking of the midthigh as determined from the scout scans on four different occasions. The CSA measurements were analysed at the same time by the same investigator after completion of the study.

Training Program

The endurance training was conducted on Concept II exercise machines designed to simulate rowing, five consecutive days each week (Monday to Friday) for five weeks at an intensity of 85 to 90% of maximum heart rate (approximately equivalent to 75% of $\dot{V}O_2max$ determined immediately prior to endurance training). Exercise duration began at 40 minutes per session and increased by five minutes each week until 60 minutes of continuous rowing was achieved. The Concept II ergometers provide similar physiological demands to the Gjessing ergometer and imitate actual sculling (Chenier & Leger, 1986). The intensity of exercise was individually monitored each session using Sport Tester heart rate monitors (Polar Electro Ltd.). These instruments have been previously reported to be valid and stable (Leger & Thivierge, 1988).

Resistance training consisted of low velocity, circuit resistance (approximately 1.05 rad · s^{-1}) training using hydraulic exercise equipment (Hydra-Fitness Industries) four times a week (Monday, Wednesday, Friday and Sunday) for five weeks. Twelve stations were arranged in a circuit alternating between an upper and lower body station. Exercise at each station consisted of two sets of 30 seconds of maximal exercise and 30 seconds rest. Training progressed from 2 to 3 circuits after the first week with approximately 5 minutes rest between circuits. Unfortunately, the hydraulic cylinders which provide the resistance do not constitute a true isokinetic loading system. However, average angular velocity can be approximated with this equipment from the range of motion and number of repetitions performed in a fixed time period (Bell et al., 1988; Petersen et al., 1988). Thus, 10 repetitions of knee extension and flexion were required in 30 s of exercise for each subject throughout a total of 180 degrees in both directions. All repetitions and cylinder settings for each testing session were recorded. The resistance setting was increased when the number of repetitions exceeded the required number of ten on two consecutive training sessions. The angular velocity of training was approximated for all the exercise stations in the circuit. However, these approximations depended on the type of movement and range of motion allowed by the equipment station.

Eleven equipment stations were followed in the order listed below which specifically involved the upper and lower body muscle groups used for rowing: 1). bilateral seated hip and knee extension; 2). seated bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 3). unilateral seated knee extension and flexion; 4) standing bilateral elbow flexion and extension with shoulder abduction and adduction; 5). bilateral seated hip and knee extension; 6). supine bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 7). unilateral seated knee extension and flexion; 8). unilateral seated elbow flexion and extension; 9). unilateral reclined hip abduction and adduction; 10). supine unilateral horizontal shoulder abduction and adduction; 11). unilateral supine hip flexion and extension. Also, situps were included after equipment station 11. All training sessions were monitored by a supervisor who timed the exercise and relief intervals and provided consistent verbal encouragement.

Statistical Analysis

A separate 2 x 4 ANOVA (group vs time) with repeated measurements was utilized to compare the two training groups during a five week pre-control period and after 5 and 10 weeks of training on the following variables: knee extension peak torque, knee extension total work, cross sectional area of the quadriceps femoris muscle, maximal oxygen consumption, submaximal heart rate and submaximal blood lactate response to exercise. Multiple comparisons were conducted with a Duncan post hoc analysis. Alpha was preset at $p < 0.05$.

Results

A significant group by time interaction occurred for maximal oxygen consumption, submaximal heart rate and submaximal blood lactate levels. Table 3.1 shows that endurance training significantly increased both absolute ($l \cdot min^{-1}$) and relative ($ml \cdot kg^{-1} \cdot min^{-1}$) $\dot{V}O_2max$ and decreased submaximal heart rate and blood lactate levels to the same extent for both groups of subjects regardless of the training sequence followed. A significant decrease in $\dot{V}O_2max$ and increase in submaximal responses to exercise was observed after subsequent LVR training in group ES. No significant changes occurred with these variables in group SE after just the LVR training. A significant increase in submaximal heart rate response occurred between week -5 and week 0 in both groups. No significant change in body weight occurred in either group during training.

A significant interaction effect was also observed for CSA of the quadriceps femoris muscle. Table 3.2 shows that CSA increased similarly in both training groups with LVR training ($P < 0.05$). Endurance training produced a significant decrease in CSA only when preceded by LVR training (group SE).

A significant group by time interaction occurred for knee extension peak torque at all angular velocities and for total work during four knee extensions at 1.05 and 2.09 rad $\cdot$ s^{-1}. LVR training significantly increased knee extension peak torque at 1.05 and 2.09 rad $\cdot$ s^{-1} in both groups SE and ES regardless of the sequence (Figure 3.1 and 3.2). Peak torque at 2.09 rad $\cdot$ s^{-1} was significantly decreased after endurance training in group ES. Total work from 4 knee extensions was significantly increased at 1.05 and 2.09 rad $\cdot$ s^{-1} with LVR training in group ES (Figure 3.3) but not group SE (Figure 3.4).

Discussion

Many athletes, such as rowers, require a combination of both strength and endurance to be successful (Secher, 1980; Mahler et al., 1985). These appear to be somewhat exclusive characteristics as endurance training has been shown to have little effect on the aquisition of strength (Hickson, 1980; Dudley & Djamil, 1985) while resistance training has shown little or no change in aerobic power (Hickson, 1980; Hurley et al., 1984b; Dudley & Djamil, 19875). However, there is some research that found an increase in $\dot{V}O_{2}max$ with weight training (Stone et al, 1983) and high velocity, circuit resistance training (Bell et al., 1988; Petersen et al., 1988). The present study showed that the endurance and low velocity, circuit resistance training programs produced anticipated improvements in aerobic fitness and strength measurements, respectively.

The endurance training program utilized in this study was primarily designed to enhance submaximal and maximal aerobic performance. Similar improvements were observed for $\dot{V}O_2max$ and submaximal heart rate response with endurance training in both groups. The increase in $\dot{V}O_2max$ is thought to be primarly due to an improved cardiac output (ie. improved stroke volume) as well as peripheral factors within the active muscle mass (Clausen, 1977; Saltin & Rowell, 1980; Holloszy & Coyle, 1984). Submaximal heart rate changes after endurance training may be due in part to an increase in stroke volume output, a decrease in the sympathetic/parasympathetic ratio, a decrease in catecholamine response and/or an increase in mechanical efficiency during exercise (Clausen, 1977; Henriksson, 1977; Rosiello et al., 1987). The relative improvement in submaximal blood lactate response exceeded both other variables and may suggest a greater improvement in muscle oxidative capacity (Davies et al., 1981; Hurley et al., 1984a; Hardman et al, 1986). It may also suggest a decrease in lactate production (Favier et al., 1986), clearance rate (Donovan & Brooks, 1983) or both.

The low velocity, circuit resistance (LVR) training produced gains in peak torque which were specific at or near the training velocity. Research has shown that velocity controlled resistance training can result in adaptations that are specific to the velocity of training (Caiozzo et al., 1981; Kanehisa & Miyashita, 1984). The mechanisms responsible for strength increases are likely due to changes in the nervous system or morphological and biochemical changes in the muscle (Thorstensson et al., 1976; MacDougall et al., 1977; Costill et al., 1977; Luthi et al., 1986; Sale, 1987). The changes in muscle are thought to be secondary to adaptations in the nervous system with short term resistance training (< 3 weeks) such as conducted in the present study (Moritani & DeVries, 1979; Hakkinen & Komi, 1983). However, significant increases in cross sectional area of the quadriceps femoris muscle was observed in both groups with LVR training and these increases have been shown to be positively related to an increase in strength (Ikai & Fukunaga, 1968).

The measurement of peak torque does not necessarily represent an improvement in the amount of work completed during a maximal muscular contraction (Rosler et al., 1986). Thus, total work during four maximal knee extensions was assessed. The improvements in total work were similar to peak torque in group ES indicating both an increase in both the highest point acheived during a single maximal contraction as well as the total work or area under the torque vs angle curve with LVR training. However, group SE did not exhibit the same response. The lack of a statistically significant change in total work after LVR training in group SE may have been due to the large variance and small sample size as improvements were apparent in some individuals.

There were no significant differences observed between the two sequential training programs followed in the present study. However, this study and other research (Bell et al., 1988) indicates that resistance training and endurance training conducted in sequential programs results in some physiological alterations that appear to be sequence dependent. When LVR training preceeded endurance training (group SE), peak torque was not significantly decreased after endurance training despite a significant decline in cross sectional area of the quadriceps muscle. Maximal oxygen consumption ($\dot{V}O_2max$) a: submaximal exercise responses were not significantly altered with LVR training in group SE. Thus, the present results seem to indicate that peak torque was somewhat preserved in group SE with subsequent endurance training in a rowing mode, especially at fast angular velocities. This finding may also have occurred because strength is easier to maintain (Berger, 1965; Morehouse, 1967) than endurance (Fox et al., 1975; Henriksson & Reitman, 1977; Otto et al., 1978).

Conversely, peak torque in group ES was significantly decreased after endurance training (at 2.09 rad · s^{-1}). Thus, endurance was unable to preserve peak torque at this velocity. In addition, a significant decrease in $\dot{V}O_2max$ and significant increases in submaximal exercise responses after subsequent LVR training. Cross sectional area of the quadriceps femoris muscle was not significantly decreased after endurance training in group ES. Peak torque, total work and cross sectional area of knee extensors were significantly increased after LVR training. Despite the improvement in strength, this training sequence (ES) resulted in a significant decline of any aerobic endurance gains that were initially developed. Research has shown that the activities of key enzymes such as citrate synthase, succinate dehydrogenase and cytochrome oxidase, which are related to the oxidative capacity of muscle, exhibit a short half-life after cessation of endurance training (Henriksson & Reitman, 1977; Houston et al., 1979; Coyle et al., 1984). Other research has shown that increases in $\dot{V}O_2max$ and submaximal endurance observed with endurance training return to almost pre-training levels during detraining (Fox et al., 1975; Fox et al., 1977). Furthermore, MacDougall et al (1979) has shown a reduction in mitochondrial volume density with resistance training. This research supports the present findings which found a decrement in endurance after LVR training in group ES.

Therefore, it seems that conducting LVR training prior to endurance training in a rowing mode may facilitate some maintenance of peak torque while building aerobic fitness with subsequent endurance training. The opposite training sequence resulted in significant decrements in endurance gains developed prior to the LVR training program. The suggestion of performing resistance training prior to endurance training is supported by other work (Bell et al., 1988) which showed that high velocity resistance training prior to endurance training may also be the preferred training sequence.

In summary, training for strength and endurance by athletes who require development of both can be conducted in sequential training programs. The adaptations to low velocity, circuit resistance training or endurance training in isolation do not seem to be affected by sequencing. However, there seems to be a smaller decrement in peak torque after endurance training when LVR training precedes endurance training. This results in some maintenance of peak torque especially at fast angular velocities. The sequence of endurance prior to LVR training may result in a decrease of peak torque after endurance training and a decrease in endurance after resistance training. Therefore, this investigation suggests that LVR training prior to endurance training may have some advantage and has implications when designing training programs for athletes that require the development of both strength and endurance. It is also possible that strict sequencing may not be optimal and some maintenance training is required when training a different fitness component.

References

Bell, G., Petersen, S., Quinney, H. A. & Wenger, H. A. (1988). Sequencing of endurance and high velocity strength training. Canadian Journal of Sport Sciences, 13(4), 214-219.

Berger, R. (1965). Comparison of the effect of various weight training loads on strength. Research Quarterly, 36, 141-146.

Caiozzo, V., Perrine, J. & Edgerton, V. (1981). Training-induced alterations of the in vivo force-velocity relationship of human muscle. Journal of Applied Physiology, 51(3), 750-754.

Campbell, D. & Stanley, J. (1963). Experimental and Quasi-Experimental Designs for Research. Boston: Houghton Misslin Company.

Chenier, D. & Leger, L. (1986). $\dot{V}O_2$ peak with 2 rowing ergometers (Concept II and Gjessing) and a single scull on water. (Abstract). Canadian Journal of Applied Sport Sciences, 8P.

Clausen, J. (1977). Effect of physical training on the cardiovascular adjustments to exercise in man. Physiological Reviews, 57(4), 779-815.

Costill, D., Coyle, E., Fink, W., Lesmes, G. & Witzmann, F. (1979). Adaptations in skeletal muscle following strength training. Journal of Applied Physiology, 46(1), 96-99.

Coyle, E., Feiring, D., Rotkis, T., Cote, R., Roby, F., Lee, W. & Wilmore, J. (1981). Specificity of power improvements through slow and fast isokinetic training. Journal of Applied Physiology, 51(6), 1437-1442.

Davies, K., Packer, L. & Brooks, G. (1981). Biochemical adaptations of mitochondria, muscle, and whole-animal respiration to endurance training. Archives of Biochemistry and Biophysics, 209(2), 539-554.

Donovan, C. & Brooks, G. (1983). Endurance training affects lactate clearance, not lactate production. Journal of Applied Physiology, 244(7), E83-E92.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Farrel, M. & Richards, J. (1986). Analysis of the reliability and validity of the kinetic communicator exercise device. Medicine and Science in Sports and Exercise, 18(1), 44-49.

Favier, R., Constable, S., Chen, M. & Holloszy, J. (1986). Endurance exercise training reduces lactate production. Journal of Applied Physiology, 61(3), 885-889.

Fox, E., Bartels, R., Klinzing, J. & Ragg, K. (1977). Metabolic responses to interval training programs of high and low power output. Medicine and Science in Sports, 9(3), 191-196.

Fox, E., Bartels, R., Billings, R., O'Brien, R., Bason, R. & Mathews, D. (1975). Frequency and duration of interval training programs and changes in aerobic power. Journal of Applied Physiology, 38(3), 481-484.

Hakkinen, K. & Komi, P. (1983). Electromyographic changes during strength training and detraining. Medicine and Science in Sport and Exercise, 15(6), 455-460.

Hardman, A., Williams, C. and Wootton, S. (1986). The influence of short-term oxygen uptake, submaximal endurance and the ability to perform brief, maximal exercise. Journal of Sport Science, 4, 109-116.

Henriksson, J. (1977). Training induced adaptation of skeletal muscle and metabolism during submaximal exercise. Journal of Physiology, 270, 661-675.

Henriksson, J. & Reitman, J. (1977). Time course of changes in human skeletal muscle succinate dehydrogenase and cytochrome oxidase activities and maximal oxygen uptake with physical activity and inactivity. Acta Physiologica Scandinavica, 99, 91-97.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Holloszy, J. & Coyle, E. (1984). Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. Journal of Applied Physiology, 56(4), 831-838.

Houston, M., Bentzen, H. & Larsen, H. (1979). Interrelationships between skeletal muscle adaptations and performance as studied by detraining and retraining. Acta Physiologica Scandinavica, 105, 163-170.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Hurley, B., Hagberg, J., Allen, W., Seals, S., Young, J., Cuddihee, R. & Holloszy, J. (1984a). Effect of training on blood lactate levels during submaximal exercise. Journal of Applied Physiology, 56(5), 1260-1264.

Hurley, B., Seals, D., Ehsani, A., Cartier, L., Dalsky, G., Hagberg, J. and Holloszy, J. (1984b). Effects of high intensity strength training on cardiovascular function. Medicine and Science in Sport and Exercise, 16(5), 483-488.

Ikai, M. & Fukunaga, T. (1968). Calculation of muscle strength per unit cross sectional area of human muscle by means of ultrasonic measurement. Internationale Zeitschrift fur Angewante Physiologie Einschliesslich Arbeits Physiologie, 26, 26-32.

Kanehisa, H. & Miyashita M. (1983). Specificity of velocity in strength training. European Journal of Applied Physiology, 52, 104-106.

Leger, L. & Thivierge, M. (1988). Heart rate monitors: validity, stability, and functionality. The Physician and Sportsmedicine, 15(5), 143-151.

Luthi, J., Howald, H., Claassen, H., Rosler, K., Vock, P. & Hoppeler, H. (1986). Structural changes in skeletal muscle tissue with heavy-resistance exercise. International Journal of Sports Medicine, 7, 123-127.

Mahler, D., Parker, H. & Andresen, D. (1985). Physiologic changes in rowing performance associated with training in collegiate women rowers. International Journal of Sports Medicine, 6(4), 229-233.

MacDougall, D., Sale, D., Moroz, J., Elder, G., Sutton, J. & Howald, H. (1979). Mitochondrial volume density in human skeletal muscle following heavy resistance training. Medicine and Science in Sports, 11, 164-166.

MacDougall, D., Ward, G., Sale, D. & Sutton, J. (1977). Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. Journal of Applied Physiology, 43(4), 700-703.

Morehouse, C. (1967). Development and maintenance of isometric strength of subjects with diverse initial strengths. Research Quarterly, 38, 449-456.

Moritani, T. & DeVries, H. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115-130.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance, (Abstract), Medicine and Science in Sports, 16, 184.

Otto, R., Fox, E., & Stevens, C. (1978). Metabolic responses of young women to training and maintenance/ detraining. Medicine and Science in Sports, 10(1), 52.

Petersen, S., Miller, G., Quinney, H. A. & Wenger, H. (1988). The influence of high-velocity resistance circuit training on aerobic power. Journal of Orthopaedic and Sports Physical Therapy, 9(10). 339-344.

Riedy, M., Moore, R. & Gollnick, P. (1985). Adaptive response of hypertrophied muscle to endurance training. Journal of Applied Physiology, 59(1), 127-131.

Rosiello, R., Mahler, D. & Ward, J. (1987). Cardiovascular responses to rowing. Medicine and Science in Sports and Exercise, 19(3), 239-245.

Rosler, K., Conley, K., Howald, H., Gerber, C. & Hoppeler, H. (1986). Specificity of leg power changes to velocities used in bicycle endurance training. Journal of Applied Physiology, 61(6), 30-36.

Sale, D. (1987). Influence of exercise and training on motor unit activation. Exercise and Sport Sciences Reviews, 15, 95-151.

Sale, D. (1986). Interaction between concurrent strength and endurance training. (Report Contract No. 8SE85-00082). Downsview, Ontario: Defence and Civil Institute of Environmental Medicine.

Saltin, B. & Rowell, L. (1980). Functional adaptations to physical activity and inactivity. Federation Proceedings, 39, 1506-1513.

Secher, N. (1983). The physiology of rowing. Journal of Sport Sciences, 1, 23-63.

Sigma Chemical Company (1981). The quantitative determination of pyruvic acid and lactic acid. Sigma Technical Bulletin No. 826-UV. Sigma Chemical Company: St. Louis.of Applied Physiology, 44, 17-23.

Thoden, J., Wilson, B. & MacDougall, J. (1982). Testing Aerobic Power. In MacDougall, J., Wenger, H. & Green, H. (Eds), Physiological testing of the elite athlete. Mutual Press Limited: Ottawa.

Stone, M., Wilson, G., Blessing, D. and Rozenek, R. (1983). Cardiovascular responses to short-term olympic style weight-training in young men. American Journal of Applied Sport Sciences, 8(3), 134-139.

Thorstensson, A., Hulten, B., Von Dobeln, W. & Karlsson, J. (1976). Effect of strength training on enzyme activities and fiber characteristics in human skeletal muscle. Acta Physiologica Scandinavica, 96, 392-398.

Wessel, J., Gray, G., Luongo, F., Isherwood, L. (1988). The reliability of work measurements recorded during concentric and eccentric contractions of the knee extensors. Physiotherapy Canada, In Press.

Table 3.1 Absolute and relative $\dot{V}O_2max$, submaximal heart rate (HR) and blood lactate (BLa) 5 weeks before (-5), just prior to (0), after 5 (5) and 10 (10) weeks of training in groups SE and ES.

		$\dot{V}O_2max$		Submaximal HR	Submaximal BLa
Week	Group	($l \cdot min^{-1}$)	($ml \cdot kg^{-1} \cdot min^{-1}$)	($b \cdot min^{-1}$)	($mmol \cdot l^{-1}$)
-5	SE	4.24 (.03)	54.6 (0.5)	170 (1)	6.3 (0.4)
0	SE	4.31 (.04)	55.5 (0.6)	181 (1)^{a}	5.9 (0.1)
5	SE	4.23 (.03)	54.5 (0.3)	180 (1)^{a}	5.8 (0.3)
10	SE	4.42 (.03)^{ac}	56.8 (0.6)^{ac}	173 (1)^{bc}	4.5 (0.2)^{abc}
-5	ES	4.29 (.03)	53.5 (0.5)	172 (2)	5.9 (0.4)
0	ES	4.39 (.02)	54.8 (0.2)	186 (1)^{a}	6.5 (0.2)
5	ES	4.54 (.03)^{ab}	57.0 (0.4)^{ab}	175 (2)^{b}	4.6 (0.3)^{ab}
10	ES	4.27 (.02)^{c}	53.6 (0.4)^{c}	182 (1)^{ac}	5.6 (0.3)^{c}

a = significantly different from week -5, $p < 0.05$.

b = significantly different from week 0, $p < 0.05$.

c = significantly different from week 5, $p < 0.05$.

Values are means (SE).

Table 3.2 Cross sectional area of quadriceps femoris muscle 5 weeks before (-5), just prior to (0), after 5 (5) and after 10 (10) weeks of training in groups SE and ES.

	Cross Sectional Area (cm^2)			
	Before Training		After Training	
Group	-5 weeks	0 weeks	5 weeks	10 weeks
SE	90.6 (1.2)	90.8 (1.0)	93.0 (0.7)[a]	90.3 (1.3)[b]
ES	95.5 (0.6)	95.1 (0.5)	94.2 (0.6)	96.7 (0.4)[b]

a = significantly different from week -5, $p < 0.05$.

b = significantly different from week 5, $p < 0.05$.

Values are means (SE).

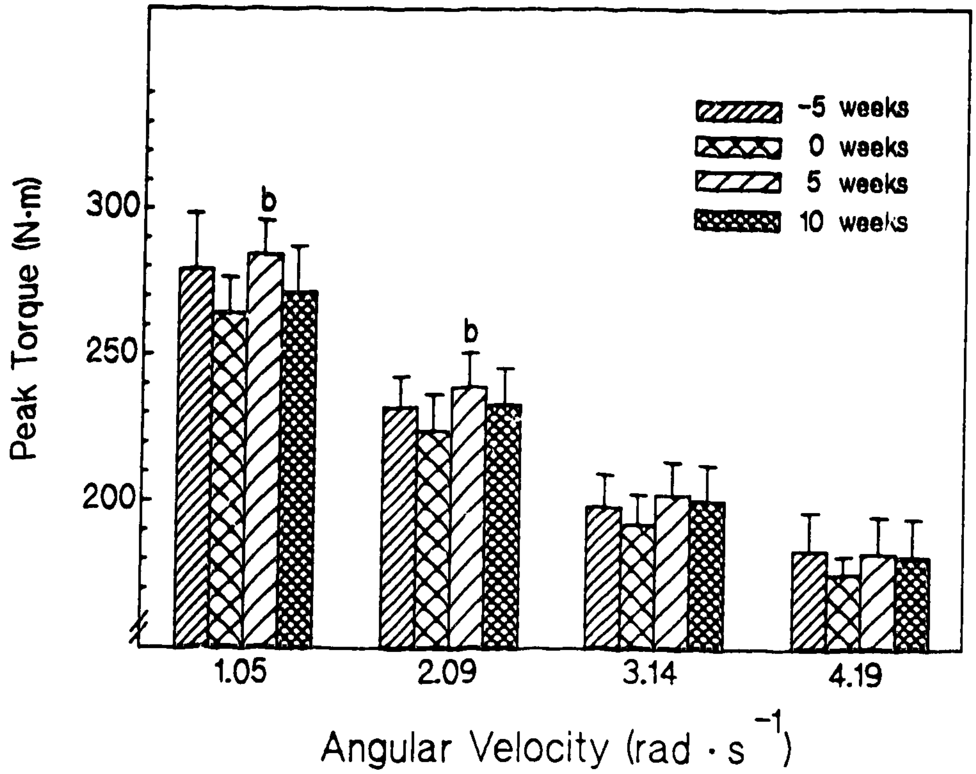

Figure 3.1 Peak torque for right knee extension at four angular velocities 5 weeks before (-5), just prior to (0), after 5 and 10 weeks of training for group SE.
Values are means (SE).
b = significantly different from week 0 at the same angular velocity, $p < 0.05$.

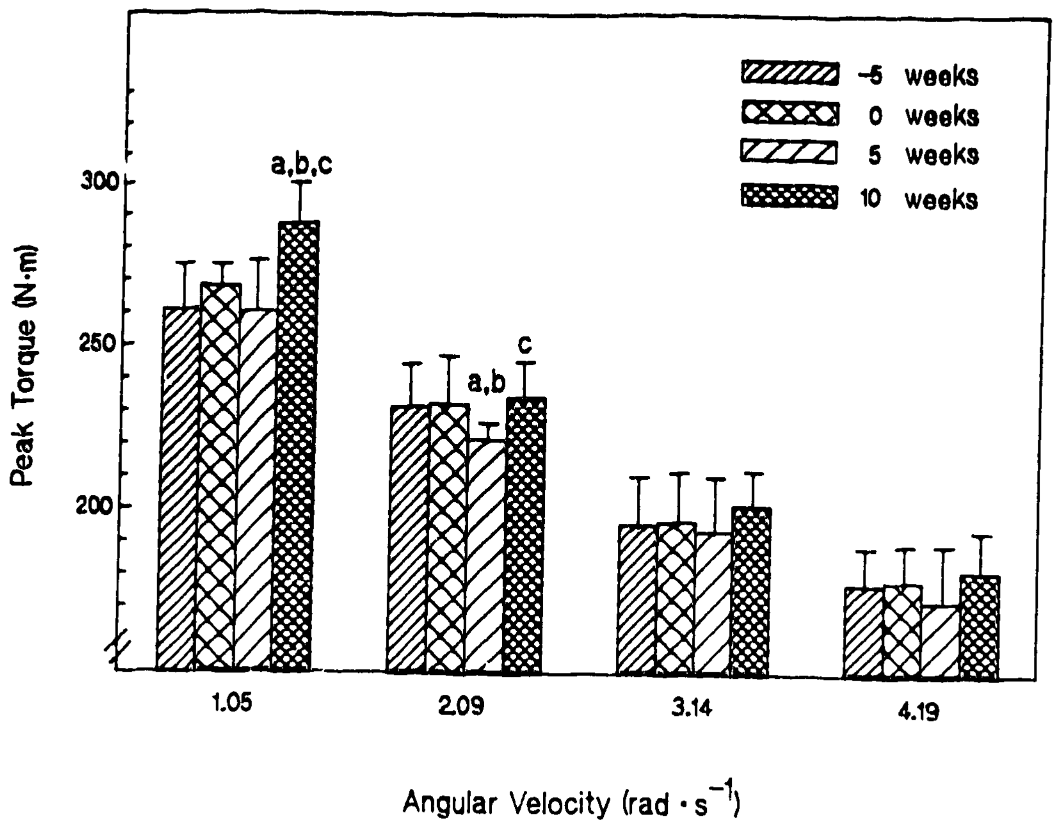

Figure 3.2 Peak torque for right knee extension at four angular velocities 5 weeks before (-5), just prior to (0), after 5 and 10 weeks of training for group ES.

alues are means (SE).

a = significantly different from week -5 at the same angular velocity, $p < 0.05$.

b = significantly different from week 0 at the same angular velocity, $p < 0.05$.

c = significantly different from week 5 at the same angular velocity, $p < 0.05$.

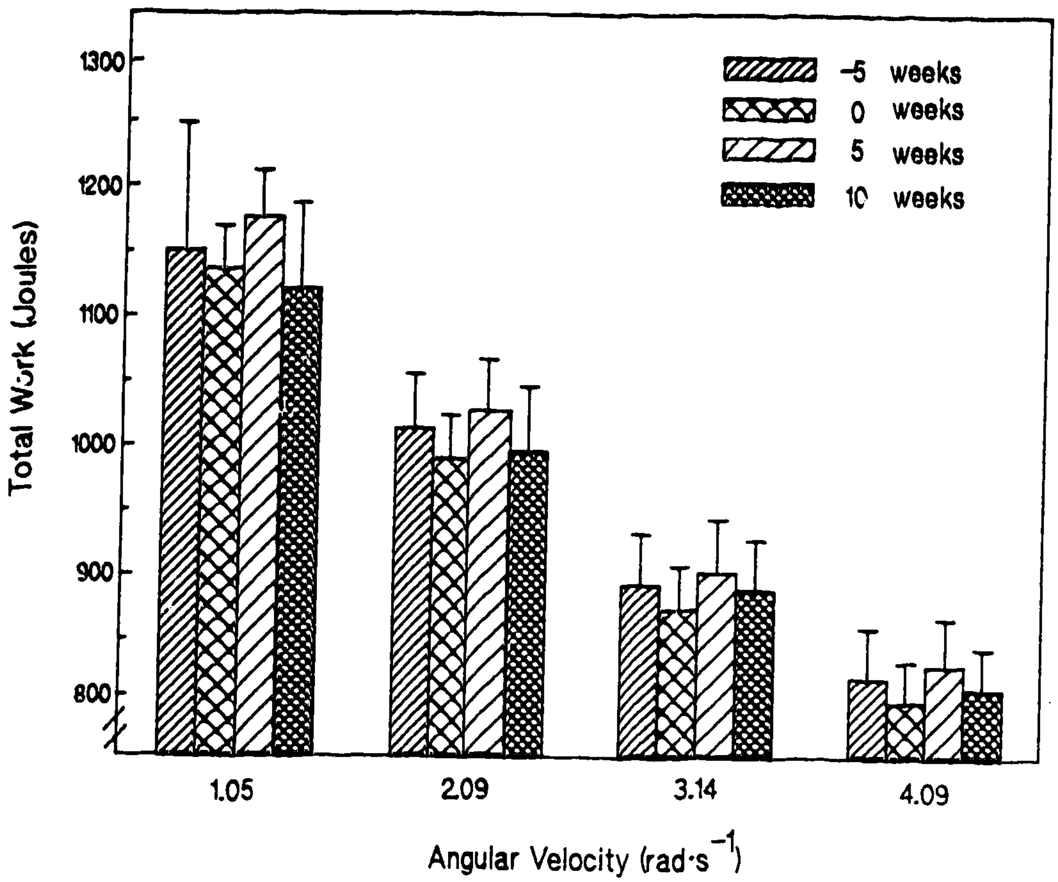

Figure 3.3 Total work during four right knee extensions at four angular velocities 5 weeks before (-5), just prior to (0), after 5 and 10 weeks of training for group SE. Values are means (SE).

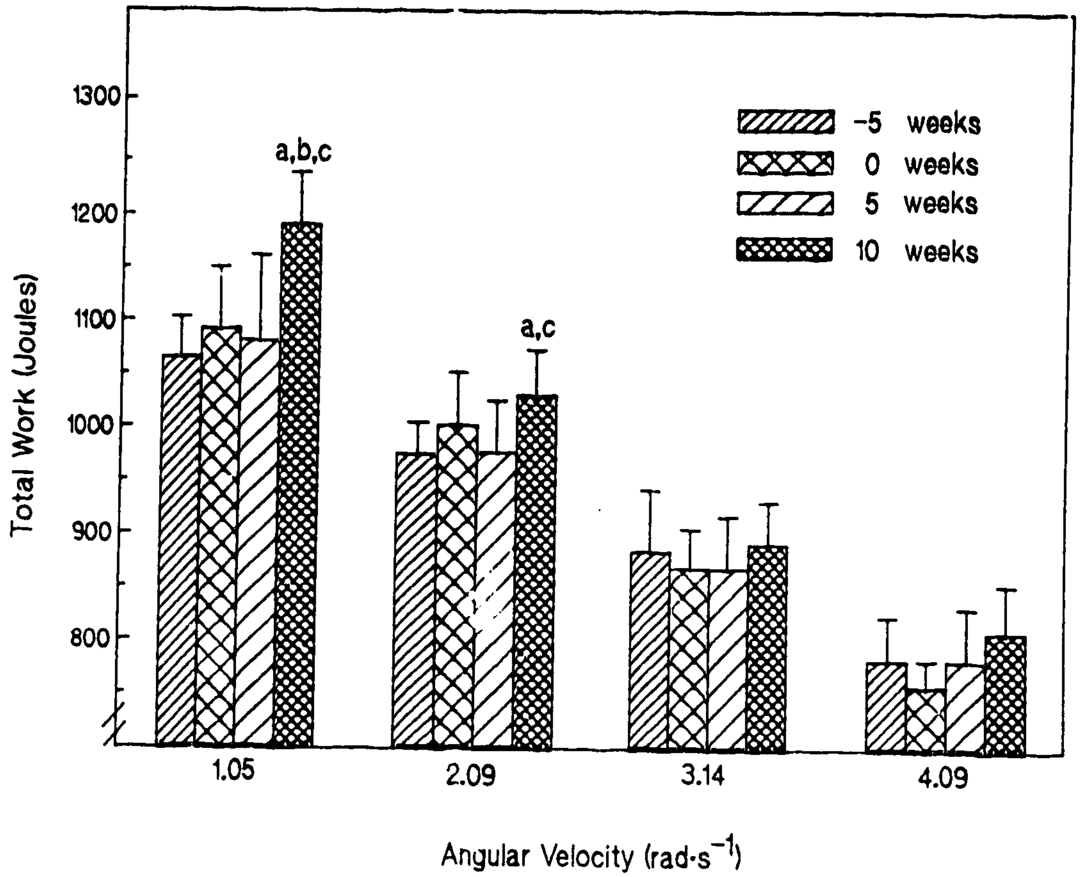

Figure 3.4 Total work during four right knee extensions at four angular velocities 5 weeks before (-5), just prior to (0), after 5 and 10 weeks of training for group ES. Values are means (SE).

a = significantly different from week -5 at the same angular velocity, $p < 0.05$.

b = significantly different from week 0 at the same angular velocity, $p < 0.05$.

c = significantly different from week 5 at the same angular velocity, $p < 0.05$.

Chapter 4

PAPER 3: PHYSIOLOGICAL ADAPTATIONS TO CONCURRENT ENDURANCE TRAINING AND LOW VELOCITY RESISTANCE TRAINING

Introduction

Earlier work by Hickson (1980) showed that untrained subjects performing concurrent endurance training and resistance training had a plateau in strength (1 RM) at 7 weeks followed by a slight decrease after 8 weeks of training while maximal oxygen consumption continued to increase. Dudley and Djamil (1985) also reported a compromise in knee extension peak torque at fast angular velocities (but not slow) after simultaneous endurance and high velocity resistance training. This research led to the idea that an interference effect was operating during concurrent training for both strength and endurance. The result was a compromise in strength development. Further support for the existence of this interference phenomena was provided by Hunter et. al. (1987). However, Nelson et al. (1984) and Sale (1987) observed no significant differences between strength training alone and training for both strength and endurance. Thus, there is some controversy regarding the physiological adaptations to concurrent resistance and strength training.

Therefore, the purpose of this investigation was to evaluate strength (knee extension peak torque and total work), cross sectional area of the quadriceps femoris muscle and aerobic endurance (maximal oxygen consumption and submaximal responses to an absolute workload) after concurrent endurance training and low velocity, circuit resistance training.

Methods

Subjects and Experimental Design

Sixteen volunteers from the University of Alberta Rowing Club signed informed consent and agreed to participate in this research project. Two of these subjects dropped out for medical reasons not related to the study. The mean (± SD) age, height and weight were 24.8 (± 3.5) years, 178.4 (± 9.1) cm and 77.2 (± 8.5) kg, respectively. The subjects were given a complete explanation of the testing protocols and training program. A quasi-experimental time-series design which was chosen allows periodic measurements and the introduction of an experimental change into this time-series of measurements (Campbell & Stanley, 1963). This design was chosen as it was difficult to convince athletic populations to act as controls for extended periods without training and it allows the stability of dependent measures to be assessed prior to training.

The subjects undertook 12 weeks of concurrent endurance and low velocity, circuit resistance training and were tested on all dependent variables 3 weeks before, twice immediately prior to training and at 3 week intervals during training. The training program consisted of 3 resistance and 3 endurance workouts a week for 12 weeks. The subjects received one day rest prior to each testing session and all subjects were asked to completely refrain from any other training during this study.

Testing Procedures

Submaximal response to a fixed absolute workload and maximal oxygen consumption ($\dot{V}O_2max$) were assessed during an incremental test to fatigue on an ergometer for rowing exercise (Gjessing Ergorow, Bergen, Norway) using open circuit spirometry. Ventilation and expiratory oxygen and carbon dioxide content were collected and analyzed every 30 seconds with a Beckman Metabolic Measurement Cart (MMC). A Rudolph high capacity breathing valve and mouthpiece allowed the subject to inspire ambient air and the use of a noseclip ensured that all expired air was collected and analyzed. Calibration of the MMC was conducted before and after each test with gases of known concentration. Heart rate was recorded during the last 15 s of each minute with an electrocardiograph (ECG, Cambridge model VS4).

The submaximal test consisted of six minutes of continuous rowing exercise at a power output of 125 W by maintaining flywheel revolutions at 500 revolutions per minute against a resistance of 14.7 N (stroke rate of 24 to 26 strokes per minute). Previous work revealed a plateau in oxygen consumption and heart rate to occur for all subjects using this submaximal protocol. A small (1 ml) blood sample was taken from an antecubital vein one minute after cessation of the submaximal test. One half of a milliliter was deproteinized in 4% perchloric acid (2 ml), centrifuged for 10 minutes, stored at -80 degrees Celcius and later analysed for lactate levels (Sigma Chemical Co. Kit 826 UV, 1981). No change in resting blood lactate or hematocrit was observed during training. The subjects subsequently resumed rowing at the previous stroke rate and flywheel revolutions per minute at a resistance of 17 N (power output = 143 W) for one minute and the resistance was increased by 2.5 N every minute for 6 minutes. During the final two workloads, the resistance was also increased by 2.5 N but the subjects were requested to increase stroke rate and flywheel revolutions to a maximum. The subjects were verbally encouraged to continue at this maximal rate beyond eight minutes if possible. However, no subject was able to continue past 10 minutes. The main criterion for achieving $\dot{V}O_2max$ was a peak or plateau in oxygen consumption with increasing poweroutput and secondary criteria included reaching age predicted or known maximum heart rate, exceeding a respiratory exchange ratio of 1.15, or until volitional exhaustion occurred (Thoden et al., 1982). Test-retest reliability coefficients between -6 and -3 days for $\dot{V}O_2max$ and maximum heart rate as well as submaximal heart rate, blood lactate and oxygen consumption are listed in Appendix C.

Strength of the right knee extensors was assessed as the highest point on the torque vs angle curve (peak torque) and total work during four muscular contractions (gravity compensated) at an angular velocity of 1.05 rad $\cdot$ s^{-1} on a Kinetic Communicator (Kin Com) isokinetic dynamometer. The dynamometer was calibrated prior to and after the study. The validity and reliability of the dynamometer has been previously established (Farrel & Richards, 1986). The testing mode was concentric for both knee extension and knee flexion. Only knee extension was reported for this study as it was emphasized in training and is a major muscle group involved in rowing. A minimum force of 20 N with no pause between contractions was chosen and the range of motion was 95 to 10 degrees from full extension as some subjects found it difficult to reach full knee extension in the sitting position. The subjects were seated and secured with a strap around the waist at the level of the pelvis and a strap around the thigh just proximal to the knee joint. The subjects were allowed to grasp the seat during the test. The input axis of the dynamometer was visually aligned with the lateral epicondyle of the femur and the lever arm secured to the lower tibia just proximal to the malleolus allowing for maximal lever arm length. The subjects were allowed a submaximal warmup at each angular velocity and were then required to perform 4 maximal contractions throughout the full range of limb movement. Verbal motivation was consistently provided and this protocol was maintained for all testing sessions. Test-retest reliability coefficients for peak torque and total work between day -5 and -2 are given in Appendix C.

Cross sectional area of the quadriceps femoris was determined using computerized tomography (CT) scanning (Model 9800, General Electric Medical Systems). The subjects were scanned immediately prior to training and after 6, 9 and 12 weeks of training. Previous research has shown no change in cross sectional area of the quadriceps femoris muscle prior to training using similar subjects. Inter- and intra-rater reliability of the scanning measurement and intra-rater reliability for landmarking has been shown to be high (Bell et al., 1989). A 1 cm scan (120 kVp, 100 mA, 2 s) was taken at a point halfway between the crest of the greater trochanter and the lateral epicondyle of the femur. A small line (1.5 cm long) was drawn on the thigh with an indelible marker and it was periodically remarked during the study. The site was checked by measurement prior to every scan to ensure accuracy. The subjects were supine during scanning with their arms at the side and their feet approximately 15 cm apart allowing some clearance (2 to 3 cm) between the right and left thigh. Both thighs were visually positioned parallel to the scanning platform using foam wedges under the hips, calves and ankles to ensure that the scan was taken perpendicular to the thighs. Black and white contact prints of the images were taken and the boundary of the quadriceps femoris muscle group was outlined prior to computer analysis of cross sectional area on the General Electric 9800 computer planimetry system. All analyses were conducted by the same investigator.

Training Program

The endurance training program involved continuous rowing exercise 3 days a week (Monday, Wednesday, Friday) on Concept II rowing machines at an intensity equivalent to 85 to 90% of maximum heart rate (approximately 75% $\dot{V}O_2max$). Individual heart rates were monitored by the subjects using Sport Tester portable heart rate monitors (Polar Electro Ltd.). The accuracy of these monitors has been previously reported (Leger & Thivierge, 1988). Duration of training was initially set at 40 minutes and was progressively increased by 5 minutes every three weeks until 55 minutes of continuous rowing was acheived. The subjects were allowed to take a short break (3 to 4 minutes) halfway through the session to stretch. All training sessions were supervised.

Low velocity, circuit resistance training was performed on variable resistance hydraulic equipment (Hydra-Fitness Industries) 3 times a week for 12 weeks on alternate days (Tuesday, Thursday, Sunday) to endurance training. The resistance training velocity was approximately 1.05 rad $\cdot$ s^{-1}. Since the hydraulic cylinders do not provide a true isokinetic loading system, average angular velocity was approximated from the range of motion and the number of repetitions performed in a fixed time period. For example, 10 repetitions of knee extension and knee flexion (total range of 180 degrees) were completed in 30 seconds by varying the hydraulic cylinder settings which approximates 1.05 rad $\cdot$ s^{-1}. These approximations depended on the type of movement, the range of motion and the hydraulic cylinder settings allowed by the equipment station. Thus, the number of repetitions ranged between 8 and 12 in 30 seconds for all subjects. The subjects completed 2 sets at each station with a work to rest ratio of 1:1. Training was conducted in a circuit fashion, beginning with 2 circuits of 12 stations and adding an extra 1/3 of the circuit every 3 weeks over the 12 week program. The subjects were requested to begin at a different equipment station each training session. Three minutes of rest were allowed between each circuit.

The following 12 equipment stations were included in the circuit: 1). unilateral seated knee extension and flexion; 2). supine bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 3). bilateral seated hip and knee extension; 4). unilateral seated elbow flexion and extension; 5). unilateral seated knee extension and flexion; 6). supine bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 7). unilateral reclined hip abduction and adduction; 8). supine bilateral horizontal shoulder abduction and adduction; 9). unilateral supine hip flexion and extension; 10). seated bilateral elbow extension and flexion with horizontal shoulder abduction and adduction; 11). bilateral seated hip and knee extension; 12). standing bilateral elbow flexion and extension with shoulder abduction and adduction. Situps were also included. All training was timed and monitored by a supervisor and each subject recorded their own repetitions and resistance settings.

Statistical Analysis

A one-way analysis of variance (ANOVA) with one factor repeated (time) was utilized to determine significant changes during training on the following variables: knee extension peak torque, total work during four knee extensions, cross sectional area of the quadriceps femoris, maximal oxygen consumption, maximal heart rate, submaximal heart rate, submaximal blood lactate and submaximal oxygen consumption. Multiple comparisons were conducted with a

Duncan post hoc analysis. Level of significance was preset for all analyses at $p < 0.05$.

Results

Table 4.1 shows that both absolute and relative $\dot{V}O_2max$ were significantly higher on all testing sessions after training compared to before training. Also, $\dot{V}O_2max$ was significantly increased after 6 weeks of training compared to after 3 weeks but no further increases were observed after 9 and 12 weeks of training. Furthermore, $\dot{V}O_2max$ was significantly different between -4 weeks and -3 days. Maximum heart rate showed a significant decrease after 3 and 12 weeks of training compared to before training (-3 days). No significant change in body weight was observed during training.

Submaximal oxygen consumption ($\dot{V}O_2$), heart rate (HR) and blood lactate (BLa) were all significantly decreased after training (Table 4.2). Submaximal $\dot{V}O_2$ was significantly lower after 9 weeks compared to before training and was significantly lower than all other scores after 12 weeks of training. Submaximal HR was significantly lower after 3, 6, and 9 weeks compared to before training and was significantly lower than all other scores after 12 weeks of training. Blood lactate response to submaximal exercise was also significantly decreased after 3, 6, 9 and 12 weeks compared to all scores before training. Also, blood lactate levels after 12 weeks of training were significantly lower than after 3 and 6 weeks of training.

Table 4.3 shows that knee extension peak torque was significantly increased after 6 weeks of training compared to -2 days prior to training. Peak torque was significantly higher after 9 and 12 weeks of training compared to week 3 and 6. Total work during four knee extensions was significantly higher after 6 weeks of training compared to before training and week 3. Also, total work was significantly higher after 9 and 12 weeks of training compared to all other scores. Cross sectional area of the quadriceps femoris muscle was significantly increased after 6, 9 and 12 weeks of training compared to before training (Table 4.4). There was no significant change in peak torque, total work or cross sectional area between week 9 and 12.

Discussion

The physiological adaptions to endurance training and resistance training are somewhat different. Aerobic endurance training promotes improvements in the central cardiorespiratory system (Clausen, 1977; Rosiello et al., 1987) and the active muscle mass (Davies et al., 1981; Hurley et al, 1984). This leads to an enhanced oxidative capacity but little or no change in strength occurs (Hickson, 1981; Dudley & Djamil, 1985). Resistance training produces neuromuscular adaptations (Sale, 1988), increases in muscle cross sectional area (Luthi et al., 1986) and increases in contractile protein content of muscle (MacDougall et al., 1980). Little or no change in maximal oxygen consumption (Hickson, 1980; Bell et al., 1989), a reduction of mitochondrial volume density (MacDougall et al., 1979) and decreases in the activity of various oxidative enzymes (Tesch, 1988) have been reported after resistance training. However, there is some evidence thatmaximal oxygen consumption can increase with circuit weight training and high velocity, circuit resistance training (Stone et al., 1983; Bell et al., 1988; Petersen et al., 1988). Thus, it seems that endurance training and resistance training produce physiological adaptations which may be antagonistic or complementary to each other.

Combined endurance training and resistance training has shown an interference effect resulting in a compromise in strength improvements but not in maximal oxygen consumption (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1987). Other studies refute the suggestion of an interference phenomena. Sale (1986) showed that gains in 1RM and repetitions at 80 % of 1RM were not impeded after concurrent endurance and strength training. However, this research utilized a one-legged training program and cannot account for changes in the central nervous system or levels of circulating hormones such as testosterone that may affect both limbs after single leg training. Nelson et al. (1984) observed no significant impairment in peak torque after simultaneous endurance and low velocity resistance training after 20 weeks in comparison to a resistance training group. No testing was conducted periodically during training and the time course of adaptation for the concurrent training group may have differed from the resistance training group.

The suggestion by one researcher (Sale, 1986) was that a threshold of training volume may exist and an interference effect may occur if this threshold is exceeded. The present study attempted to provide a concurrent endurance and resistance training program that would not exceed a training volume that may evoke an interference effect. As a result peak torque, total work and cross sectional area exhibited a progressive increase after each 3 week training phase for 9 weeks. However, these variables showed very little change during the last 3 weeks of concurrent training. This plateau in strength was observed even with an increase in the volume of resistance training. In a separate but related study (unpublished observations by S. Petersen, Appendix D), a group of active subjects undertook an identical low velocity, circuit resistance (LVR) training program at the same time as the concurrent training group in the present study. The group that conducted LVR training only showed a significant increase in knee extension peak torque, total work and cross sectional area of the quadriceps femoris muscle between week 9 and 12. Thus, the present study supports other research (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1986) that suggests some compromise in the adaptations to resistance training may occur if endurance training is performed at the same time.

The reason for the lack of increase in strength of the knee extensors during the last three weeks of concurrent endurance and LVR training may be partly due to the absence of any increase in cross sectional area of the quadriceps femoris muscle during the same time period. Research has shown that strength and muscle size are positively correlated (Ikai & Fukunaga, 1968; Maughan et al., 1983). Dudley & Fleck (1987) have also suggested that the recruitment and adaptations within the slow twitch motor units as a result of endurance training are greater than adaptations within the fast twitch motor units after resistance training during simultaneous training for both. These authors (Dudley & Fleck, 1987) have suggested that overtraining may be an additional cau[illegible] the interference phenomenon and this was a major criticism of the training regime reported by Hickson (1980) who used a excessive volume of training.

The present study used a moderate training volume and alternated endurance training and LVR training on different days and progressively increased the volume of training. Also, the subjects were athletic individuals who were used to high intensity training. Previous research has used untrained subjects. However, these improvements in experimental design did not prevent the occurrence of an interference phenomenon. Thus, a much larger increase in the volume of resistance training or a reduction in endurance training may be necessary during the latter weeks of concurrent training if a continuous increase in strength is desired.

Endurance training was also progressively increased throughout the 12 week concurrent training program. Maximal oxygen consumptions showed a significant increase after 3 and 6 weeks of training but no further increase was observed after 9 and 12 weeks. This finding was not suprising as only duration of training was progressively overloaded while the intensity of training remained the same. In a review of the interactions of intensity, frequency and duration of endurance training to improve maximal oxygen consumption, intensity of training seemed to be the most important factor (Wenger & Bell, 1986). Thus, maximal oxygen consumption plateaued after initial adaptations to endurance training. Maximum heart rate also showed a small but significant decrease after weeks 3 and 12 of training. This decrease in maximum heart rate has been previously observed with endurance training and may be the result of an increase in end diastolic volume due to an increased ventricle size, a decrease in sympathetic/parasympathetic ratio and/or a decrease sensitivity to catecholamines (Ekblom et al., 1968; Clausen, 1977).

The responses to submaximal exercise responses showed a slightly different time course compared to the changes in maximal oxygen consumption. Submaximal heart rate response at the same absolute workload was decreased after 3 weeks of training and only small decreases were observed after 6 and 9 weeks. However, a significant drop in heart rate was observed from week 9 to week 12. The primary reasons for this decrease in heart rate include at least the following: an improved stroke volume output, a decrease in the sympathetic/parasympathetic ratio, a decrease in catecholamine levels and/or an increase in mechanical efficiency of exercise (Clausen, 1977; Rowell, 1980; Rosiello et al., 1987).

The decreases in submaximal oxygen consumption coincided with the decreases in submaximal heart rate and blood lactate suggesting that a change in efficiency may have occurred. Other research has shown either no change (Fox et al., 1977) or decreases (Ekblom et al., 1968; Fox et al., 1975) in submaximal oxygen consumption. Rowing exercise has reported to be less efficient than other forms of exercise such as cycling (Hagerman et al., 1974; 1978). It is reasonable to suggest that an improvement in efficiency with rowing exercise training occurred in the present study. Thus, the changes in submaximal heart rate and blood lactate response may be partly due to an increase in the efficiency of exercise.

Submaximal blood lactate also exhibited a progressive decrease and the lowest level was acheived after 12 weeks of training. This adaptation suggests a decrease in lactate production (Favier et al., 1986), an increase in clearance (Donovan & Brooks, 1983), or an increase in oxidative capacity of muscle (Davies et al., 1981; Hurley et al., 1984; Hardman et al., 1986). However, a combination of all three mechanisms could be operating.

In summary, the present study found that performing moderate intensity, continuous endurance training and low velocity, circuit resistance training at the same time resulted in a no significant increases in strength or cross sectional area of knee extensors after 9 weeks of training (week 9 to 12). However, it is difficult to support an interference effect in strength without a similar athletic group for comparison that completed only the same resistance training program. Maximal oxygen consumption showed increases up to 6 weeks of training and no further increases occurred. However, submaximal exercise responses showed significant decreases up to 12 weeks of training resulting in a somewhat different time course of adaptation. However, the decreases in submaximal responses to exercise may be partly due to a change in efficiency of exercise and partly due to endurance training. It is suggested that athletes who conduct endurance and resistance training use either sequential training programs or adjust the volume of training to avoid a potential interference in strength develoment with concurrent training programs. Furthermore, an increase in the intensity of endurance training may be required if continuous increases in maximal oxygen consumption are desired.

References

Bell, G., Petersen, S., Quinney, H. A. & Wenger, H. A. (1988). Sequencing of endurance and high velocity strength training. Canadian Journal of Sport Sciences, 13(4), 214-219.

Bell, G., Petersen, S., Quinney, H. A., Wessel, J., Ba· all, K. (1989). Physiological adaptations to endurance and low velocity resistance training performed in a sequence. Submitted to Medicine and Science in Sports and Exercise.

Campbell, D., & Stanley, J. (1963). Experimental and Quasi-Experimental Designs for Research. Boston: Houghton Musslin Company.

Clausen, J. (1977). Effect of physical training on the cardiovascular adjustments to exercise in man. Physiological Reviews, 57(4), 779-815.

Davies, K., Packer, L. & Brooks, G. (1981). Biochemical adaptations of mitochondria, muscle, and whole-animal respiration to endurance training. Archives of Biochemistry and Biophysics, 209(2), 539-554.

Donovan, C. & Brooks, G. (1983). Endurance training affects lactate clearance, not lactate production. Journal of Applied Physiology, 244(7), E83-E92.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Ekblom, B., Astrand, P., Saltin, B., Stenberg, J. & Wallstrom, B. (1968). Effect of training on circulatory response to exercise. Journal of Applied Physiology, 24(4), 518-528.

Farrel, M. & Richards, J. (1986). Analysis of the reliability and validity of the kinetic communicator exercise device. Medicine and Science in Sports and Exercise, 18(1), 44-49.

Favier, R., Constable, S., Chen, M. & Holloszy, J. (1986). Endurance exercise training reduces lactate production. Journal of Applied Physiology, 61(3), 885-889.

Fox, E., Bartels, R., Billings, C., O'Brien, R., Bason, R. & Mathews, D. (1975). Frequency and duration of interval training programs and changes in aerobic power. Journal of Applied Physiology, 38(3), 481-484.

Fox, E., McKenzie, D. & Cohen, K. (1975). Specificity of training: metabolic and circulatory responses. Abstract. Medicine and Science in Sports 7(1), 83.

Hagerman, F., Connors, M., Gault, J., Hagerman, G. & Polinski, W. (1978). Energy expenditure during simulated rowing. Journal of Applied Physiology, 45(1), 87-93.

Hagerman, F., Fox, E., Connors, M. & Pompei, J. (1974). Metabolic response of women rowers during ergometric rowing. Abstract. Medicine and Science in Sports, 6(1), 87.

Hardman, A., Williams, C. and Wootton, S. (1986). The influence of short-term oxygen uptake, submaximal endurance and the ability to perform brief, maximal exercise. Journal of Sport Science, 4, 109-116.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Hurley, B., Hagberg, J., Allen, W., Seals, S., Young, J., Cuddihee, R. & Holloszy, J. (1984). Effect of training on blood lactate levels during submaximal exercise. Journal of Applied Physiology, 56(5), 1260-1264.

Ikai, M. & Fukunaga, T. (1968). Calculation of muscle strength per unit cross sectional area of human muscle by means of ultrasonic measurement. Internationale Zeitschrift fur Angewante Physiologie Einschliesslich Arbeits Physiologie, 26, 26-32.

Leger, L. & Thivierge, M. (1988). Heart rate monitors: validity, stability, and functionality. The Physician and Sportsmedicine, 15(5), 143-151.

Luthi, J., Howald, H., Claassen, H., Rosler, K., Vock, P. & Hoppeler, H. (1986). Structural changes in skeletal muscle tissue with heavy-resistance exercise. International Journal of Sports Medicine, 7, 123-127.

MacDougall, D., Elder, G., Sale, D., Moroz, J., & Sutton, J. (1980). Effects of strength training and immobilization on human muscle fibers. European Journal of Applied Physiology, 43, 25-34.

MacDougall, D., Sale, D., Moroz, J., Elder, G., Sutton, J. Howald, H. (1979). Mitochondrial volume density in human skeletal muscle following heavy resistance training. Medicine and Science in Sports, 11, 164-166.

Maughan, R., Watson, J. & Weir, J. (1983). Relationship between muscle strength and muscle cross sectional area in man. European Journal of Applied Physiology, 50, 309-318.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance. (Abstract), Medicine and Science in Sports, 16, 184.

Petersen, S., Miller, G., Quinney, H. A., Wenger, H. A. (1988). The influence of high-velocity resistance training on aerobic power. The Journal of Orthopaedic and Sports Physical Therapy, 9(19), 339-344.

Rosiello, R., Mahler, D. & Ward, J. (1987). Cardiovascular responses to rowing. Medicine and Science in Sports and Exercise, 19(3), 239-245.

Rowell, L. (1980). What signals govern the cardiovascular responses to exercise? Medicine and Science in Sports and Exercise, 12(5), 307-315.

Sale, D. (1986). Interaction between concurrent strength and endurance training. (Report Contract No. 8SE85-00082). Downsview, Ontario: Defence and Civil Institute of Environmental Medicine.

Sale, D. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5), S135-S145.

Sigma Chemical Company (1981). The quantitative determination of pyruvic acid and lactic acid. Sigma Technical Bulletin No. 826-UV. Sigma Chemical Company: St. Louis.of Applied Physiology, 44, 17-23.

Stone, M., Wilson, G., Blessing, D. & Rozenek, R., (1983). Cardiovascular responses to short-term olympic style weight-training in young men. Canadian Journal of Applied Sport Science, 8(3), 134-139.

Thoden, J., Wilson, B. & MacDougall, J. (1982). Testing Aerobic Power. In MacDougall, J., Wenger, H. & Green, H. (Eds), Physiological testing of the elite athlete. Mutual Press Limited: Ottawa.

Wenger, H. A. & Bell, G. (1986). The interactions of intensity, frequency and duration of exercise training on altering cardiorespiratory fitness, Sports Medicine, 3(5),346-356.

Table 4.1 Absolute and relative $\dot{V}O_2max$ and maximal heart rate (HRmax) 4 weeks before (-4) and just prior to (6 and 3 days before) training and after 3, 6, 9 and 12 weeks of training.

	$\dot{V}O_2max$ ($l \cdot min^{-1}$)	$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	HRmax ($b \cdot min^{-1}$)
-4 weeks	3.87 (.36)	50.6 (5.6)	190 (5)
-6 days	3.93 (.38)	50.8 (5.5)	189 (9)
-3 days	4.00 (.41)^{c}	51.7 (5.1)	191 (8)
3 weeks	4.18 (.39)^{a}	53.9 (5.0)^{a}	187 (6)^{d}
6 weeks	4.29 (.39)^{ab}	55.5 (5.8)^{ab}	188 (8)
9 weeks	4.30 (.39)^{ab}	55.5 (5.3)^{ab}	189 (7)
12 weeks	4.31 (.36)^{ab}	55.7 (4.8)^{ab}	187 (7)^{d}

a = significantly different from all scores before training. $p < 0.05$.

b = significantly different from week 3, $p < 0.05$.

c = significantly different from -4 weeks, $p < 0.05$.

d = significantly different from -3 days, $p < 0.05$.

Values are means (SD).

Table 4.2 Submaximal oxygen consumption ($\dot{V}O_2$), heart rate (HR), blood lactate (BLa) and 4 weeks before (-4) and just prior to (-6 and -3 days) training and after 3, 6, 9 and 12 weeks of training.

	Submaximal		
	$\dot{V}O_2$ ($l \cdot min^{-1}$)	HR ($b \cdot min^{-1}$)	BLa ($mmol \cdot l^{-1}$)
-4 weeks	2.58 (.15)	153 (12)	3.0 (1.2)
-6 days	2.50 (.10)	152 (16)	3.1 (0.5)
-3 days	2.52 (.12)	151 (13)	2.9 (0.6)
3 weeks	2.47 (.12)^{e}	143 (14)^{a}	2.1 (0.5)^{a}
6 weeks	2.43 (.08)^{e}	140 (13)^{a}	1.8 (0.4)^{a}
9 weeks	2.40 (.13)^{a}	139 (14)^{a}	1.5 (0.5)^{a}
12 weeks	2.30 (.08)^{d}	132 (13)^{d}	1.1 (0.6)^{abc}

a = significantly different from all scores before training, $p < 0.05$.

b = significantly different from week 3, $p < 0.05$.

c = significantly different from week 6, $p < 0.05$.

d = significantly different from all other scores, $p < 0.05$.

e = significantly different from -5 weeks, $p < 0.05$.

Values are means (SD).

Table 4.3 Peak torque for one knee extension and total work during 4 knee extensions at 1.05 rad · s^{-1} 4 weeks (-4) and just prior to (-5 and -2 days) training and after 3, 6, 9 and 12 weeks of training.

	Peak Torque (N·m)	Total Work (Joules)
-4 weeks	237 (14)	988 (53)
-5 days	235 (13)	978 (30)
-2 days	230 (15)	964 (61)
3 weeks	238 (8)	988 (38)
6 weeks	243 (12)^{d}	1039 (56)^{ab}
9 weeks	258 (18)^{abc}	1089 (68)^{abc}
12 weeks	260 (12)^{abc}	1095 (53)^{abc}

a = significantly different from all scores before training. $p < 0.05$.

b = significantly different from week 3, $p < 0.05$.

c = significantly different from week 6, $p < 0.05$.

d = significantly different from -2 days, $p < 0.05$.

Values are means (SD).

Table 4.4 Cross sectional area of quadraceps femoris muscle just prior to (-4 days), after 6, 9 and 12 weeks of training.

Cross Sectional Area (cm^2)			
Before Training	After Training		
-4 days	6 weeks	9 weeks	12 weeks
91.3 (1.5)	93.9 (0.9)[a]	94.9 (1.3)[a]	94.0 (0.9)[a]

a = significantly different from -4 days, $p < 0.05$.

Values are means (SD).

Chapter 5

GENERAL DISCUSSION

The main purpose for these research projects was to investigate the physiological adaptations to endurance training and velocity controlled resistance raining when performed sequentially or concurrently. Also, this project provided guidelines for a practical on-land training program for oarsmen during their off-season. The rationale for conducting endurance and velocity controlled resistance training in a sequence was to avoid a potential interference in strength development as reported by some investigations when training for both was done concurrently (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1987). Other studies have shown that compensatory hypertrophied mammalian muscle responds to endurance training in a manner similar to nonhypertrophied muscle (Baldwin et al., 1977; Reidy et al., 1985). Also, endurance trained runners exhibited strength gains (1 RM) after resistance training while conducting maintenance endurance training twice a week. The gains in the endurance trained group were as great as a group of untrained subjects (Hunter et al., 1987). These findings suggest that endurance training and resistance training may be organized into a sequential training program without compromising strength or endurance gains.

There is some controversy reported in the literature with regards to simultaneous training programs involving both endurance training and resistance training. Hickson (1981), Dudley and Djamil (1985) and Hunter et al. (1987) provide support for the existence of an interference in strength gains when both endurance and resistance training programs are conducted concurrently. Other reports suggest that simultaneous training for endurance and strength are not necessarily incompatible (Nelson et al., 1984; Sale, 1986). All previous studies used untrained subjects. The physiological adaptations to a concurrent endurance and resistance training program with athletes who typically perform both has not been investigated.

A summary of findings from each separate research project follows.

Study 1 : Physiological adaptations to endurance and high velocity resistance training performed in a sequence.

Sequencing of high velocity, circuit resistance training prior to endurance training (group SE) resulted in a significant progressive increase in maximal oxygen consumption after both training programs, a significant decrease in submaximal heart rate and blood lactate after endurance training and a significant increase knee extension and flexion peak torque after high velocity resistance training. The increases in peak torque occurred at or near the angular velocity of high velocity resistance training and these improvements were maintained with subsequent endurance training. The opposite sequence of endurance training prior to high velocity resistance training (group ES) exhibited a significant increase in maximal oxygen consumption and a significant decrease in submaximal heart rate and blood lactate response after endurance training. The increase in maximal oxygen consumption was maintained with subsequent high velocity resistance training but the decreases in submaximal exercise responses were returned to levels observed before endurance training. Knee extension peak torque showed no significant increases with either endurance or high velocity resistance training. However, a significant increase in knee flexion peak torque after high velocity resistance training did occur in group ES. The conclusion from this study was that if the goal of this off-season training program was to provide the greatest improvement in both endurance and strength immediately prior to the pre-season then the preferred sequence of training may be high velocity resistance training prior to endurance training.

Study 2 : Physiological adaptations to endurance and low velocity resistance training performed in a sequence.

This study showed that the adaptations observed after low velocity, circuit resistance training and endurance training were independent of the sequence of training followed. However, when low velocity resistance training was conducted prior to endurance training (group SE), there was no significant decrease in peak torque or total work despite a significant decrease in cross sectional area of the quadriceps femoris muscle after endurance training. Furthermore, maximal oxygen consumption and submaximal exercise responses were not significantly altered with low velocity resistance training but were improved with endurance training in group SE. The opposite sequence of endurance training prior to low velocity resistance training (group ES) produced significant increases in maximal oxygen consumption and decreases in submaximal exercise responses with endurance training. These improvements returned to pre-training values after low velocity resistance training. Also, peak torque at 2.09 rad $\cdot$ s^{-1} was significantly decreased after endurance training in group ES. Thus, group ES completed the entire training program with significant increases in strength but the endurance training improvements returned to levels observed before the start of training. Thus, the sequence of low velocity resistance training prior to endurance training may have some advantage as this sequence showed some maintenance of the adaptations observed after resistance training while showing increases in maximal oxygen consumption and decreases in submaximal exercise responses with subsequent endurance training.

Study 3: Physiological adapatations to concurrent endurance and low velocity resistance training.

Concurrent low velocity, circuit resistance training and endurance training produced increases in peak torque, total work and cross sectional area of knee extensors after 6 and 9 weeks of training. No further improvements were observed between 9 and 12 weeks. Maximal oxygen consumption showed no further significant increase after 6 weeks of training presumably because there was no progressive increase in the intensity of endurance training. Submaximal oxygen consumption and heart rate showed significant decreases between 3 and 6 weeks and 9 and 12 weeks. Thus, it seems that simultaneous low velocity resistance training and endurance training may result in a compromise in knee extension peak torque and total work after 9 weeks and this compromise may be partly due to a lack of increase in muscle cross sectional area.

Methodological Considerations

These research projects have some methodological concerns that warrant further discussion. The type of endurance training was continuous, moderate intensity exercise and was designed primarily to enhance the ability to perform submaximal exercise and secondarily to improve, but not peak, maximal oxygen consumption at this time of the athletes' training calendar (ie. off-season). The mode of endurance training was rowing exercise as the subjects were oarsmen and testing was conducted in a similar mode using a slightly different ergometer so a more precise quantification of power output could be made. However, the metabolic responses to exercise on both rowing machines have been shown to be similar (Chenier & Leger, 1986).

Circuit resistance training was conducted on hydraulic resistance training equipment which does not completely control the velocity of limb movement to the same extent as an isokinetic dynamometer. Thus, a stronger individual may achieve slightly higher limb velocities than a weaker individual at the same resistance setting. However, a variety of exercise stations are available with this type of equipment and a number of different upper and lower body muscle groups can be exercised providing a complete resistance training program. Strength testing was conducted on an isokinetic dynamometer (ie. Cybex or KinCom) which may not be completely specific to the mode of resistance training. However, isokinetic dynamometers provide accommodating resistance and are currently the most valid and reliable instrument to assess the adaptations to velocity controlled resistance training.

Right knee extension (and flexion in study 1) was chosen to represent the changes with resistance training. The adapations in the left limb were assumed to be similar. The selection of knee extension was justified as it was an emphasized movement in resistance training and is an important movement in rowing. No assessment of any upper body muscle groups was made. However, the upper and lower body received a similar volume of resistance training as there was an equal number of upper and lower body equipment stations.

Computer tomography scanning was used to measure any changes in the cross sectional area of the quadriceps femoris muscle group after resistance training. This method was used in contrast to measuring the change in area of individual fast and slow twitch muscle fibers obtained from muscle biopsies. The changes in cross sectional area determined from CT scanning may reflect changes in connective tissue and vasculature as well as muscle mass. Thus, the CT scanning was used as a gross measure of the anatomical cross sectional area of the quadriceps femoris muscle.

The subjects involved in this project were a combined group of light and heavy weight oarsmen and rowing experience ranged from one to several years at the club level. Thus, the generalizability of this research project is limited to this athletic group and the sample size was small which reduces statistical power.

Finally, a consideration of experimental design must be made when using athletes as subjects since it is difficult to convince a similar sample to act as controls during a training study as these individuals must continue to train to be involved in their sport. In study 1, a control group of eight different oarsmen who conducted maintenance endurance and resistance training for 5 weeks was compared to the 5 week endurance training and resistance training programs of both experimental groups. However, the control period did not coincide in time with the training periods. A time-series design was chosen for study 2 to eliminate the need for a separate control group, but provide a control period of maintenance training prior to the experimental intervention (training). However, this pre-control period was conducted over the Christmas season and it was difficult to control the subjects' activities during this time. A time-series design was also chosen for study 3 with the addition of a second set of testing prior to the start of training. The second set of tests allowed further evaluation of the stability and reliability of the dependent measures prior to the training intervention.

Summary

The physiological adaptations to endurance and resistance training programs differ somewhat depending on the order or sequence of training and the velocity of resistance training performed. It seems that prior endurance training is not a necessary requirement for adaptations to high or low velocity resistance training or vice versa. However, prior endurance training may reduce adaptations in knee extension peak torque when followed by subsequent high velocity resistance training. Based on the present results, it is suggested that conducting resistance training prior to endurance training may be preferred. Further support for this suggestion is that strength is easier to maintain than endurance (Berger, 1965; Morehouse, 1967; Fox et al., 1975; Henriksson & Reitman, 1977; Otto et al., 1978). Concurrent endurance training and low velocity resistance training was shown to produce a compromise in knee extension peak torque, total work and cross sectional area of the quadriceps femoris muscle after 9 weeks of training. Therefore, it is suggested that if training for both strength and aerobic endurance are to be conducted during the same training phase and/or longer than 9 weeks, then some form of sequential training p ogram may be preferred to a concurrent training program.

Applications and Further Research

The applications of this research project were specifically aimed at providing a physiologically sound off-season, on-land training program for the Edmonton and University of Alberta rowing clubs. A typical off-season training program for these athletes has traditionally involved resistance training and endurance training as strength and endurance are important physiological components of rowing. However, this research has implications for athletes involved in other sports (hockey, cycling, selected track and field events, etc.) who may benefit from resistance training and endurance training during certain times of their annual training calendar.

Further research is necessary to determine the adaptations to sequential endurance training and resistance training while attempting to maintain other fitness components previously developed. Research on the effects of performing different types of endurance training (ie. interval training) and resistance training (ie. free weights) in sequential or concurrent training programs is suggested if different types of training are utilized by the athlete. Further research using concurrent endurance training and resistance training of different velocities as well as varying the volume and intensity of training in an attempt to avoid a potential compromise in strength is suggested. Also, the physiological mechanisms underlying the interference phenomena and whether it occurs to the same extent in upper body muscle groups warrants further research.

References

Baldwin, K., Cheadle, W., Martinez, O. & Cooke, D. (1977). Effect of functional overload on enzyme levels in different types of skeletal muscle. Journal of Applied Physiology, 42, 312-317.

Berger, R. (1965). Comparison of the effect of various weight training loads on strength. Research Quarterly, 36, 141-146.

Chenier, D. & Leger, L. (1986). $\dot{V}O_2$ peak with 2 rowing ergometers (Concept II) and Gjessing) and a single scull on water. (Abstract). Canadian Journal of Applied Sport Sciences, 8P.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Fox, E., Bartels, R., Billings, R., O'Brien, R., Bason, R. & Mathews, D. (1975). Frequency and duration of interval training programs and changes in aerobic power. Journal of Applied Physiology, 38(3), 481-484.

Henriksson, J. & Reitman, J. (1977). Time course of changes in human skeletal muscle succinate dehydrogenase and cytochrome oxidase activities and maximal oxygen uptake with physical activity and inactivity. Acta Physiologica Scandinavica, 99, 91-97.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Morehouse, C. (1967). Development and maintenance of isometric strength of subjects with diverse initial strengths. Research Quarterly, 38, 449-456.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance, (Abstract), Medicine and Science in Sports, 16, 184.

Otto, R., Fox, E., & Stevens, C. (1978). Metabolic responses of young women to training and maintenance/ detraining. Medicine and Science in Sports, 10(1), 52.

Riedy, M., Moore, R. & Gollnick, P. (1985). Adaptive response of hypertrophied muscle to endurance training. Journal of Applied Physiology, 59(1), 127-131.

Sale, D. (1986). Interaction between concurrent strength and endurance training. (Report Contract No. 8SE85-00082). Downsview, Ontario: Defence and Civil Institute of Environmental Medicine.

APPENDIX A

REVIEW OF RELATED LITERATURE

The nature of a sporting event influences how an optimal training program is designed. It is generally accepted that a sport such as rowing demands strength, endurance and anaerobic power (Secher, 1980; Hagerman & Staron, 1983; Clarkson et al., 1984). Off-season training for oarsmen typically involves strength and endurance development which provides a base for intense power training during the pre-competitive season (Hagerman et al., 1978; Secher, 1980; de Koning et al., 1984; Mahler et al., 1985).

Muscular Strength

Muscular strength is usually defined as the amount of force or tension a muscle or a muscle group can exert against a resistance at a specified velocity during a maximal voluntary contraction (MVC) (Knuttgen & Kraemer, 1987). Strength exercises are usually classified as being isometric (static), isotonic (concentric and eccentric) or isokinetic (concentric and eccentric). Isometric exercise involves the application of force or development of muscular tension against an immovable resistance with no change in the external length of the muscle; isotonic exercise requires the generation of muscular tension during shortening or lengthening with a constant force and is similar to a concentric contraction which simply means muscle shortening during contraction; eccentric exercise refers to the lengthening of the muscle while developing tension; and, isokinetic exercise, which involves the application of force at a controlled velocity. In athletic training it is difficult to perform "pure" isometric or isotonic contractions as the human body is a complex system composed of tendons, joints and levers which make it impossible to achieve precise contractile characteristics such as those observed in isolated muscle preparations. Furthermore, mechanical limitations of devices designed to control velocity limit the ability to perform true isokinetic muscle contractions.

The general goal of strength training for sport is to improve the development and application of muscular force. This can be accomplished through various types of resistance exercises designed to overload the muscle groups involved. Sale and MacDougall (1981) state that strength training should be specific in regards to movement patterns, velocity of movement, muscular contraction type and force. Velocity controlled resistance training equipment attempts control of movement velocity, simulates movement patterns often found in various sports such as rowing, and allows maximal concentric muscle contractions throughout the entire range of limb movement (Hislop & Perrine, 1967; Watkins & Harris, 1983). A limitation of this type of training is the absence of an eccentric component to the muscular contraction (with the exception of the Kin-Com isokinetic dynamometer), however, Martindale and Robertson (1984) state that the contribution of eccentric muscle contraction to the rowing stroke is small and de-emphasized by coaches in rowing technique training. Thus, velocity controlled resistance training can provide a specific form of strength training for athletes.

Muscle Force-Velocity Relationship

Before discussing the effects of velocity controlled training, consideration must be given to the relationship between force (or torque) and velocity (or angular velocity). The in-vitro force-velocity relationship of isolated skeletal muscle exhibits the greatest tension development at 0 velocity (isometric) with continually declining tension as velocity increases (Wilke, 1950; Hill, 1970). Perrine and Edgerton (1978) have shown that the human in-vivo torque-velocity curve for knee extensors (angle specific torque) deviates from the in-vitro curve and exhibits a plateau in torque at 192 degrees $\cdot$ s^{-1} and a slight decrease after 96 degrees $\cdot$ s^{-1}. However, Thorstensson et al. (1976) found knee extension peak torque to be highest under isometric conditions and observed a continuous decline with increasing velocities at different joint angles. These latter results follow the in-vitro force-velocity curve more closely than the data presented by Perrine and Edgerton (1978). However, Perrine and Edgerton (1978) state that torque must be expressed at a specific angle and therefore, a specific muscle length when making comparisons to the in-vitro condition. These authors used a graded dynamic knee extension to ensure that torque produced at the specified angle was maximal thus minimizing any fatigue during the initial stages of the contraction. Research which defines peak torque as the highest point achieved on the torque vs joint angle curve shows the greatest peak torque to occur at slow angular velocities (Lesmes, et al., 1978; Coyle, et al., 1981).

Various factors influence the relationship between muscle torque and angular velocity. The joint angle at which peak torque occurs for knee extensors may vary between individuals because of a mechanical advantage due to differences in bone structure, muscular development and mechanics of the knee joint. Also, peak torque may occur at an angle closer to full knee extension (anatomical neutral) with increasing angular velocity (Moffroid & Whipple, 1970; Thorstensson et al., 1976; Perrine & Edgerton, 1978). Muscle fiber composition may also influence torque at various angular velocities as individuals with greater fast twitch fiber populations have been shown to produce greater peak torque and exhibit higher correlation coefficients as angular velocity increases (Thorstensson et al., 1977; Coyle et al., 1979; Ivy et al., 1981). The physiological properties responsible for this may be due to an enhanced myofibrillar ATPase activity, calcium ion release and sequestering at sarcoplasm reticulum, and the greater phosphagen energy stores and enzyme activities within fast twitch muscle.

The force-velocity relationship of strength or power trained athletes is shifted upward in comparison to untrained individuals (Thorstensson et al., 1977) and has been shown to be influenced by specific training (Moffroid & Whipple, 1970; Lesmes et al., 1978; Caiozzo et al., 1981; Coyle et al., 1981). These observations may be due to differences in genetic potential but are probably also due to biochemical, structural or neuromuscular adaptations as a result of training.

Maximal muscle power is the product of force and velocity. Thus, power output increases with higher angular velocities until a maximum rate is achieved. Ivy et al. (1981) have shown maximum power output for knee extensors to occur between 3.14 to 4.19 rad $\cdot$ s^{-1} resulting in a mean maximal power output occurring at 3.67 rad $\cdot$ s^{-1}. These results are supported by other research which reported peak power output to occur at 4.19 rad $\cdot$ s^{-1} (Perrine & Edgerton, 1978; Kanehisa & Miyashita, 1983). It has been suggested that peak power output may occur at even greater velocities in highly trained athletes or after specific power training (Greger et al., 1979; Kanehisa & Miyashita, 1983).

Velocity Controlled Resistance Training

Some controversy still exists in the literature regarding the adaptations to velocity controlled resistance training.

However, closer examination of training velocities, dependent variables and the involved muscle groups are required before generalizations can be made. The following discussion involves research conducted on knee extensors unless otherwise stated.

Slow velocity training (below 1.75 rad · s^{-1}) has shown peak torque and angle-specific torque improvements which are greatest at slow angular velocities but extend to faster angular velocities (Moffroid & Whipple, 1970; Caiozzo et al., 1981; Coyle et al., 1981; Nobbs & Rhodes, 1986). Intermediate velocity training (at or near 3.14 rad · s^{-1}) has resulted in conflicting results. Petersen et al. (1984) found significant peak torque increase at the angular velocity used in training (3.14 rad · s^{-1}) but not at a slow angular velocities (0.52 rad · s^{-1}). Lesmes et al. (1978), Adeyanju et al. (1983) and Bell et al. (1988) found similar improvements in peak torque at both slow and intermediate angular velocities. High velocity training (at or above 4.19 rad · s^{-1}) has shown peak and angle specific torque increases which are more predominant at fast angular velocities (Caiozzo et al., 1981; Smith & Melton, 1981). On the other hand, Coyle et al. (1981) and Dudley and Djamil (1985) have shown that training at 4.19 rad · s^{-1} produced significant torque improvements which were as great at slow compared to fast angular velocities.

There is limited research which compares slow, intermediate and fast resistance training velocities on torque. However, Kanehisa and Miyashita (1984a) compared changes in average power (as opposed to peak torque) for knee extension at various angular velocities of training. These researchers found training at slow (1.05) and intermediate (3.14 rad $\cdot$ s^{-1}) velocities exhibited significant increases in average power at all five angular velocities tested (1.05 to 5.24 rad $\cdot s^{-1}$) but the improvements at 1.05 and 2.09 rad $\cdot$ s^{-1} were greater with low velocity training. Intermediate velocity training showed greater improvements at velocities that extended from 3.14 to 5.24 rad $\cdot s^{-1}$. High velocity training elicited significant improvements at angular velocities of 4.19 and 5.29 rad $\cdot$ s^{-1}, only, and these gains were slightly lower than the intermediate velocity training group.

In general, the majority of the research supports the notion that strength gains are specitic at and near the training velocities with low (<1.68 rad $\cdot$ s^{-1}) and high (> 4.19 rad $\cdot$ s^{-1}) velocity training. Intermediate velocity training (at or near 3.14 rad $\cdot$ s^{-1}) may produce improvements in peak torque at a larger range of angular velocities.

Specificity of velocity-controlled training may be a function of the inherent differences in the muscle groups tested and/or the adaptability of the muscle to the type of training program followed. Kanehisa and Miyashita (1983b) found that intermediate velocity training of elbow flexors resulted in power increases which were greater with light loads while slow velocity training resulted in significant increases with the heaviest loads only. Intermediate velocity training of elbow flexors did not exhibit significant improvements at high resistances. Lesmes et al., (1978), Petersen et al. (1984) and Bell et al. (1988) observed a greater relative improvement in peak torque with knee flexors compared to knee extensors with intermediate velocity resistance training. Further research is necessary to determine the factors involved in the adaptations to different velocities of resistance training and the response of different muscle groups to this type of training.

Mechanisms For Adaptations In Strength

The physiological adaptations that are responsible for strength gains occur within the muscle or nervous system. These improvements may be the result of hypertrophy, increases in connective tissue, biochemical adaptations or enhanced recruitment and/or synchronization of motor units (Tesch, 1988; Stone, 1988; Sale, 1988). Also, a neural tension-limiting mechanism may be operating at high resistance, low velocity contractions that may be altered with training (Perrine & Edgerton, 1978).

MacDougall (1986) stated two possible mechanisms that may be responsible for the increase in muscle size (hypertrophy) with resistance training: an increase in the tension development by muscle during training that produces a central nervous system signal resulting an increase in the uptake of amino acids and the synthesis of contractile protein; and/or, the breakdown or damage of muscle and connective tissue during forceful muscle contractions experienced during training producing an overshoot in protein synthesis during rest periods between training sessions. The overall result would be in increase in muscle size.

Athletes involved in heavy resistance training (ie. bodybuilders) exhibit a high degree of hypertrophy in comparison to untrained subjects (MacDougall et al., 1979; 1982). Resistance training has produced an increase in cross-sectional area of both type I and II fibers, with the greatest degree of hypertrophy occurring in the type II fibers (Thorstensson, 1976; MacDougall et al., 1979; Tesch et al., 1987). The increased size of both fiber types may be due to the slower rate of muscle contraction with low velocity, high resistance exercise allowing increased recruitment of both fiber types. Also, the "size principle" of motor unit recruitment dictates that slow twitch are recruited before fast twitch muscle fibers. The ultrastructural changes accompanying the increase in fiber area are an increase in myofibril cross-sectional area and an addition of actin and myosin filaments as well as a proportional increase in connective tissue (MacDougall et al., 1980; Luthi et al., 1986).

Research has shown increases in fast twitch muscle fiber area with high velocity (3.14 and 5.29 rad $\cdot$ s^{-1}) resistance training but no change in slow twitch fiber area (Costill et al., 1979; Coyle et al. 1981). The reason for these latter findings may be that high velocity exercise results in a greater recruitment and a greater stress on the fast twitch motor units as the contribution of the slow twitch motor units to the generation of force becomes less when contraction time is decreased. Thus, low velocity resistance training may produce greater development of maximal tension due to the hypertrophy of both fast and slow twitch fiber types. High velocity training may not enhance maximal tension to the same extent but may produce a greater influence on the rate of tension development. However, other neural and biochemical factors have yet to be considered.

The magnitude of the increase in muscle size following strength training does not always account for the large increases in strength observed. The increase in muscle size is thought to be secondary to neural development during short term resistance training (approximately 3 weeks or less) as the main reason for the observed increases in strength (Moritani & DeVries, 1979; Hakkinen & Komi, 1983). It has also been shown that learning and other psychological factors can influence strength assessments (Ikai &

Steinhaus, 1961; Coyle et al., 1981; Rutherford & Jones, 1986).

Research involving integrated electromyography (IEMG) has shown strength increases which are greatest in the first few weeks of training (Moritani & DeVries, 1979; Hakkinen & Komi, 1983). An increase in motor unit excitability (reflex potentiation), decreases in twitch tension and contraction time (Cracraft & Petajan, 1977; Sale et al., 1982; 1983), as well as enhancement of motor unit synchronization (Milner et al., 1975) have been shown to occur with various resistance training programs in different muscle groups. The observed increases in strength may result from increased activation of prime movers, greater involvement of synergists and an increased inhibition of antagonists (Sale, 1986; 1987). Also, Duchateau and Hainaut (1984) compared isometric to fast dynamic strength training. These researchers found that isometric training resulted in greater maximal tetanic twitch force and muscle power while dynamic training exhibited greater increases in maximal rate of tetanic twitch and single twitch tension development, and maximal velocity of shortening. Thus, the contractile kinetics of muscle may be preferentially adapted with specific resistance training. These findings imply that there may be considerable involvement of the nervous system with velocity specific strength gains observed during training.

Perrine and Edgerton (1978) have hypothesized that a tension-limiting mechanism exists which limits tension development at low velocities and high tension. Caiozzo et al. (1981) stated that this mechanism may be especially altered with low velocity, high resistance training as evidenced by the large improvements observed at low angular velocities. Intermediate and high velocity training seems to produce a more uniform improvement which could be due to alterations in synchronization and recruitment of muscle fiber units (Caiozzo et al., 1981). Burke and Edgerton (1975) stated that the relative involvement of different types of motor units is altered during movements that require both great force and/or velocity and this effect can be developed with training. Thus, velocity controlled resistance training may influence neural control properties of skeletal muscle and may partly explain the velocity specific adaptations in peak torque that have been observed. Similar strength changes observed with widely different training velocities may be the result of neural adaptations which are more general in response. Further research is necessary to distinguish the mechanisms responsible and the inconsistencies observed in the adaptations to different resistance training velocities.

Changes in biochemical components of muscle after resistance training have included increases in resting concentrations of adenosine triphosphate (ATP), creatine phosphate (CP), creatine and glycogen (MacDougall et al., 1977). Cellular enzyme activities involved in ATP turnover or glycolytic function such as myokinase, phosphorylase, phophofructokinase, creatine phosphokinase have also shown increases in vastus lateralis muscle after resistance training (Thorstensson et al., 1976; Costill et al., 1979). It is unlikely that resting phosphagen concentrations may significantly contribute to the increase in a single, maximal muscle contraction but would contribute to a greater anaerobic alactic energy supply during short duration, multiple contractions such as during sprinting. Perry (1974) and Barany (1967) suggested that magnesium stimulated ATPase and the release and uptake of calcium from sarcoplasmic reticulum may reflect biochemical changes that can have an effect on strength. Myofibrillar ATPase activity has shown adaptability to power training on a cycle ergometer (Belcastro et al., 1981) and slight improvements have been observed with five weeks of hydraulic resistance training (Bell et al., 1989). However, other research has failed to show any intramuscular enzyme changes which could be associated with increased strength even though fiber size was significantly enhanced (Houston et al., 1983; Tesch, 1987; Tesch et al., 1987). These findings could be the result of a "dilution effect" as a result of an increase in muscle contractile proteins. The existance of biochemical changes which may influence the torque/velocity curve with different training velocities cannot be ruled out.

Aerobic Endurance

Aerobic endurance may be defined as the capacity to perform rhythmic muscular work for prolonged periods of time using energy supplied primarily through aerobic sources. More specifically, endurance has been regarded as the ability to work at intensities less than maximal as opposed to working at the maximal rate of the aerobic system. Maximal work intensities may involve considerable anaerobic energy contribution as evidenced by the high production of lactic acid (Costill et al., 1973).

Previously, it was thought that the measurement of maximal oxygen consumption ($\dot{V}O_2max$) was the best predictor of endurance performance (Costill et al., 1967; Wyndham et al., 1969). However, it has since been shown that endurance athletes can exhibit similar $\dot{V}O_2max$ but can vary greatly in endurance performance and athletes with similar endurance performances can have disimilar $\dot{V}O_2max$ (Houston et al., 1974; Henriksson & Reitman, 1977; Costill et al., 1973). Thus, a constant maximal oxygen consumption may not reflect adaptations in endurance capacity (Saltin & Rowell, 1980; Sprynarova et al., 1980). Furthermore, endurance training can produce improvements in the respiratory capacity of muscle which far exceed improvements in $\dot{V}O_2max$ (Nordesjo, 1974, Davies et al., 1981; Hurley et al., 1984; Hardman et al., 1986).

Attempts to measure endurance have included the following: submaximal exercise responses to fixed and/or absolute work loads (Moore et al., 1987; Hardman et al., 1986; Hurley et al., 1984; Hagberg et al., 1980; Hickson et al., 1978); exercise time to exhaustion (Costill et al., 1973; Volkov et al., 1975; Sprynarova et al., 1980; Hardman et al., 1986); anaerobic threshold (ventilation and/or lactate threshold) (MacDougall, 1977; Davis et al., 1979; Denis et al., 1982; McLellan & Skinner, 1985); and, a test of aerobic capacity (Boulay et al., 1984). Submaximal endurance, when defined as work performed at intensities less than maximal that elicit steady state physiological responses, can be easily assessed with a performance test at an absolute or relative workload of a fixed duration (Costill et al., 1973; Hickson et al., 1978; Hagberg et al., 1980) or as a part of an incremental performance test (Hardman et al., 1986; Moore et al., 1987). Physiological responses to submaximal exercise have shown greater relative increases with endurance training of moderate intensity (approximatley 75 to 80 % $\dot{V}O_2max$) and long duration (greater than 30 minutes) compared to the relative increases in $\dot{V}O_2max$ (Hurley et al., 1984; Hardman et al., 1986). This observation has been primarily attributed to an enhanced respiratory capacity of the trained muscle and, secondarily, to changes in the central circulatory system (Davies et al., 1981; Hardman et al., 1986).

The mechanisms responsible for the physiological changes which occur as a result of endurance training can be separated into central and peripheral factors. Central factors refer to the respiratory and circulatory systems including the oxygen transport system. There is some evidence that pulmonary ventilation may be a limiting factor to maximal exercise in the highly trained athlete (Dempsey et al., 1982). However, the following review will emphasize adaptations in cardiovascular system and muscle observed with endurance training.

Central changes in the cardiovascular system result in the following changes at rest: cardiac muscle hypertrophy characterized by an increased ventricular cavity and normal or increased ventricular wall thickness (Shapiro, 1987); increase in cardiac and skeletal muscle capillarization in the involved muscle groups (Andersen & Henriksson, 1977; Klausen et al., 1981); decrease in resting heart rate (bradycardia) due to a enhanced vagal tone (parasympathetic) and decreased sympathetic influence; increase in stroke volume at rest due to the increased ventricular volume and contractility of the heart; increase in blood volume and total amount of hemoglobin; and, a decrease in resting systolic and diastolic blood pressure (Ekblom et al., 1968; Clausen, 1977; Rowell, 1980).

Central circulatory adaptations during submaximal exercise have shown: no change or a slight decrease in oxygen consumption which is usually due to increase in mechanical efficiency (Ekblom et al., 1968; Hardman et al., 1986); a decrease in ventilatory equivalents for oxygen and carbon dioxide primarily due to a decrease in ventilation (Bhambhani & Singh, 1985); a decrease in blood glucose and muscle glycogen utilization (glycogen sparing) due to an enhanced utilization of fatty acids as fuel with no significant change in plasma free fatty acid levels (Hickson et al., 1977; Brooks & Donovan, 1983; Hurley et al., 1986); a decrease in blood lactate levels and a higher relative workload is required before lactate accumulates (Hurley et al., 1984); an increase in stroke volume and a decrease in heart rate (thus, no change or slight decrease in cardiac output); an increase in arterial-venous oxygen difference; and, no change in tqtal muscle blood flow has been reported (Clausen et al., 1977; Holloszy & Coyle, 1984; Fox et al., 1988).

The effects of endurance training on maximal exercise have produced the following: an increase in maximal oxygen consumption; a decrease in blood lactate levels after maximal endurance work (Favier et al., 1986) and/or an enhanced removal rate of blood lactate (Donovan & Brooks, 1983); no change in maximum ventilatory equivalents for oxygen or carbon dioxide (Bhambhani & Singh, 1985); enhanced maximal cardiac output as a result of an improved myocardial contractility and a reduction in peripheral resistance in the trained muscles (the increase in cardiac output is a result of the increase in stroke volume output as there is no change or a slight decrease in maximum heart rate with leg training); and, an increase in total muscle blood flow in the trained muscle; and, an increase in maximum minute ventilation (Costill et al., 1970; Clausen, 1977).

Peripheral changes with endurance training refer to the cellular adaptations which reflect respiratory capacity or oxidative potential of muscle. Adaptations to endurance training include an increase in the size, number and content of mitochondria; increases in the levels of marker enzymes for the pathways of fatty acid oxidation, the citric acid cycle and the electron transport chain; and, an increase in the enzymes involved in the malate-aspartate shuttle system in both the cytoplasm and mitochondria (Holloszy & Coyle, 1984). Also, specific mitochondrial populations have shown selective adaptations depending on the intensity of training in mammalian skeletal muscle (Martin, 1987). Endurance training has shown either no appreciable changes or slight decreases in glycolytic enzyme activities (Gollnick et al., 1972; Baldwin et al., 1977; Shantz et al., 1983). However, there is some evidence of an increase in hexokinase activity (Baldwin et al., 1977). Also, a shift in the lactate dehydrogenase isozyme profile to the heart-specific form has been observed and this would favor the conversion of lactic acid back to pyruvate which can subsequently be oxidized in the mitochondria (Karlsson et al., 1975; Apple & Rogers, 1986). Little evidence exists as to whether intracellular fatty acid stores are enhanced with endurance training. However, it is known that there is a greater oxidation of fat in the trained state as indicated by measures of muscle homogenates or estimated from respiratory exchange ratios (Holloszy & Coyle, 1984; Moore et al., 1987).

Studies have shown endurance athletes to possess a predominance of slow twitch muscle fibers of quadriceps in comparison to strength and power trained athletes or untrained individuals (Saltin et al., 1977; Thorstensson et al., 1977; Tesch & Karlsson, 1985). These differences in muscle fiber profiles observed between athletic populations may be genetic in origin as there is inconclusive evidence regarding conversion of one fiber type to another in humans as a result of training. However, the possibility of conversion of type IIb to IIa in humans exists (Jansson & Kaijser, 1977; Andersen & Henriksson, 1977; Green et al., 1979; Howald, 1982). Also, it has been shown that endurance training increases slow twitch fiber area (Gollnick et al., 1973) and an increase in the oxidative capacity of fast twitch type IIa (Jansson & Kaijser, 1977).

Maximal vs Submaximal Endurance

The majority of evidence suggests that the rate at which the cardiovascular system can deliver oxygen to the working muscles is the primary factor determining maximal oxygen consumption rather than the elevated muscle repiratory capacity (Clausen, 1977; Saltin & Rowell, 1980; Holloszy & Coyle, 1984). On the other hand, peripheral changes in muscle respiratory capacity may reflect enhanced submaximal endurance performance (Sprynarova et al., 1980; Hurley et al., 1984; Hardman et al., 1986). Research has shown that athletes can have markedly different oxidative enzyme levels with similar $\dot{V}O_2max$ and vice versa (Holloszy & Coyle, 1984; Costill et al., 1976). Furthermore, peripheral changes in muscle can occur without a change in $\dot{V}O_2max$ or, at least, the peripheral changes observed may exceed the improvements in $\dot{V}O_2max$ (Henriksson & Reitman, 1977; Davies et al., 1981; Hardman et al., 1986).

It must be noted that $\dot{V}O_2$ is determined by the product of cardiac output and arterial-venous oxygen difference which involves both central and peripheral factors. Thus, it is difficult to separate the contributions of both these components to $\dot{V}O_2max$.

Concurrent Training For Endurance And Strength

Endurance training enhances the cardiorespiratory system and the oxidative capacity of muscle (Saltin & Rowell, 1980; Holloszy & Coyle, 1984) with little or no effect on strength

(Hickson, 1980). Resistance training specifically enhances the ability of muscle to develop force and has little or no effect on endurance (Hickson, 1980; Dudley & Djamil, 1985). Hypertrophied compensatory rat skeletal muscle has shown to adapt to endurance training in a similar manner to untrained muscle (Baldwin et al., 1977; Reidy et al., 1985). Hunter et al. (1987) observed strength improvements with a group of previously endurance trained subjects while maintaining their aerobic training that were as great or greater than a group of untrained subjects who undertook the same training program. This finding may be due to the lack of strength development in the endurance group as a result of previous endurance training which does not promote strength gains.

Research has shown that simultaneous training for both endurance and strength may hinder the acquistion of strength but does not diminish endurance adaptations (Hickson, 1980, Dudley & Djamil, 1985; Hunter et al., 1987). Dudley and Fleck (1987) speculated that the lack of optimal strength development when endurance training is performed at the same time may be due to inhibition of fast twitch muscle fiber adaptation at the expense of slow twitch fiber development within the same muscle group being trained; or conversely, the enhancement of the oxidative capacity of fast twitch fibers which exceeds the increase in contractile protein content (and possibly the conversion of type IIb to type IIa); and/or, overtraining.

Sale (1986) (see also MacDougall et al., 1987 and Jacobs et al., 1987) found greater strength increases with combined strength and endurance training of one leg compared to only endurance training of the other leg. No differences were observed between legs with regards to $\dot{V}O_2max$. As a part of the same project, Jacobs et al., (1986) found increases in CS, PFK, and LDH activity which were similar in both legs. However, cross-training effects have been observed with one-legged training models and this must be considered when interpreting these results. Nelson et al. (1984) observed similar increases in $\dot{V}O_2max$ and CS activity with combined strength and endurance training compared to just training for endurance but these results were only reported before and after training with no indication of a time course in adaptation of these variables. Thus, there is some controversy regarding the physiological adaptations to concurrent training for endurance and strength.

Summary

Considered separately, the adaptations to endurance training and resistance training have been well described. Studies investigating the effect of training to improve both strength and endurance at the same time have shown a compromise in strength gains but not in maximal oxygen consumption (Hickson, 1980; Dudley & Djamil, 1985; Hunter et al., 1986). Other research found no compromise in strength gains (Nelson, 1984; Sale , 1986). There has been virtually no research investigation the physiological adaptations to a sequential endurance and resistance training program.

References

Adeyanju, K., Crews, T. & Meadors, W. (1983). Effects of two speeds of isokinetic training on muscular strength, power and endurance. Journal of Sports Medicine, 23, 352-356.

Andersen, P. & Henriksson, J. (1977a). Capillary supply of the quadriceps femoris muscle of man: Adaptive response to exercise. Journal of Physiology, 270, 677-690.

Andersen, P. & Henriksson, J. (1977b). Training induced changes in the subgroups of human type II skeletal muscle fibers. Acta Physiologica Scandinavica, 99, 123-125.

Apple, F. & Rogers, M. (1986). Skeletal muscle lactate dehydrogenase isozyme alterations in men and women marathon runners. Journal of Applied Physiology, 61(2), 477-481.

Baldwin, K., Cheadle, W., Martinez, O. & Cooke, D. (1977). Effect of functional overload on enzyme levels in different types of skeletal muscle. Journal of Applied Physiology, 42, 312-317.

Barany, M. (1967). ATPase activity of myosin correlated with speed of muscle shortening. Journal of General Physiology, 50, 197-216.

Belcastro, A., Campbell, C., Bonen, A. & Kirby, R. (1981). Adaptation of human skeletal muscle myofibril ATPase activity to power training. Australian Journal of Sports Medicine, 13, 93-97.

Bell, G., Snydmiller, G. Neary, P., Quinney, H. (1989). The effect of high and low velocity resistance training on anaerobic power output in cyclists. Journal of Human Movement Studies, In Press.

Bell, G., Petersen, S., MacLean, I., Quinney, H. A. & Reid, J. (1989). The effect of high velocity resistance training on peak torque, cross sectional area and myofibrillar atpase activity. Submitted to The Journal of Sports Medicine and Physical Fitness.

Bell, G., Petersen, S., Quinney, H. A. & Wenger, H. A. (1988). Sequencing of endurance and high velocity resistance training. Canadian Journal of Sport Sciences, In Press.

Bell, G., Petersen, S., Quinney, H. A., Wessel, J. & Bagnall, K. (1988). The effect of endurance and low velocity resistance training performed in a sequence. Submitted to Medicine and Science in Sports and Exercise.

Boulay, M., Hamel, P., Simoneau, J. Lortie, G., Prud'homme, D. & Bouchard, C. (1984). A test of aerobic capacity: description and reliability. Canadian Journal of Applied Sport Sciences, 9(3), 122-126.

Bhambhani, Y. & Singh, M. (1985). The effects of three training intensities on VO_2max and V_E/VO_2 ratio. Canadian Journal of Applied Sport Sciences, 10(1), 44-51.

Brooks, G. & Donovan, C. (1983). Effect of endurance training on glucose kinetics during exercise. American Journal of Physiology, 244, E505-E512.

Burke, R. & Edgerton, V. (1975). Motor unit properties and selective involvement in movement. Exercise and Sport Sciences Reviews, 3, 31-81.

Caiozzo, V., Perrine, J. & Edgerton, V. R. (1981). Training-induced alterations of the in vivo force-velocity relationship of human muscle. Journal of Applied Physiology, 51(3), 750-754.

Campbell, D. & Stanley, J. (1963). Experimental and quasi-experimental designs for research. Rand McNally and Company: Chicago.

Chenier, D. & Leger, L. (1986). $\dot{V}O_2$ peak with 2 rowing ergometers (Concept II and Gjessing) and a single scull on water. (Abstract). Canadian Journal of Applied Sport Sciences, 8P.

Clarkson, P., Graves, J., Melchionda, A., Johnson, J. (1984). Isokinetic strength and endurance and muscle fiber type of elite oarswomen. Canadian Journal of Applied Sport Sciences, 9(3), 127-132.

Clausen, J. (1977). Effect of physical training on cardiovascular adjustments to exercise in man. Physiological Reviews, 57(4), 779-815.

Costill, D. (1967). The relationship between selected physiological variables and distance running performance. Journal of Sports Medicine, 7, 61-66.

Costill, D. (1970). Metabolic responses during distance running. Journal of Applied Physiology, 28(3), 251-255.

Costill, D., Coyle, E., Fink, W., Lesmes, G. & Witzmann, F. (1979). Adaptations in skeletal muscle following strength training. Journal of Applied Physiology, 46(1), 96-99.

Costill, D., Daniels, J., Evans, W., Fink, W., Krahenbuhl, G. & Saltin, B. (1976). Skeletal muscle enzymes and fiber composition in male and female track athletes. Journal of Applied Physiology, 40, 149-154.

Costill, D., Thomason, H. & Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. Medicine and Science in Sports, 5(4), 248-252.

Cote, C., Simoneau, J., Lagasse, P., Boulay, M., Thibault, M., Marcotte, M. & Bouchard, C. (1988). Isokinetic strength training protocols: do they induce skeletal muscle fiber hypertrophy? Archives of Physical Medicine and Rehabilitation, 69, 281-285.

Coyle, E., Feiring, D., Rotkis, T., Cote, R., Roby, F., Lee, W. & Wilmore, J. (1981). Specificity of power improvements through slow and fast isokinetic training. Journal of Applied Physiology, 51(6), 1437-1442.

Cracraft, J. & Petajan, J. (1977). Effect of muscle training on the pattern of firing of single motor units. American Journal of Physical Medicine, 56(4), 183-194.

Davies, K., Packer, L. & Brooks, G. (1981). Biochemical adaptations of mitochondria, muscle, and whole-animal respiration to endurance training. Archives of Biochemistry and Biophysics, 209(2), 539-554.

Davis, J., Frank, M. Whipp, B., Wasserman, K. (1979). Anaerobic threshold alterations caused by endurance training in middle-aged men. Journal of Applied Physiology, 46(6), 1039-1046.

de Koning, F., Vos, J., Binkhorst, R. & Vissers, A. (1984). Influence of training on the force-velocity relationship of the arm flexors of active sportsmen. International Journal of Sports Medicine, 5, 43-46.

Dempsey, J., Hanson, P., Pegelow, D., Claremont, A. and Rankin, J. (1982). Limitations to exercise capacity and endurance. Canadian Journal of Applied Sport Sciences, 7(1), 4-13.

Denis, C., Fouquet, P., Geyssant, A. and Lacour, J. (1982). Effect of 40 weeks of endurance training on the anaerobic threshld. International Journal of Sport Sciences, 3, 208-214.

Donovan, C. & Brooks, G. (1983). Endurance training affects lactate clearance, not lactate production. Journal of Applied Physiology, 244(7), E83-E92.

Duchateau, J. & Hainaut, K. (1984). Isometric or dynamic training: Differential effects on mechanical properties of a human muscle. Journal of Applied Physiology, 56(2), 296-301.

Dudley, G. & Djamil, R. (1985). Incompatibility of endurance- and strength training modes of exercise. Journal of Applied Physiology, 59(5), 1446-1451.

Dudley, G. & Fleck, S. (1987). Strength and endurance training: Are they mutually exclusive? Sports Medicine, 4, 78-85.

Ekblom, B., Astrand, P., Saltin, B., Stenberg, J. & Wallstrom, B. (1968). Effect of training on the circulatory response to exercise. Journal of Applied Physiology, 24(4), 518-528.

Farrel, M. & Richards, J. (1986). Analysis of the reliability and validity of the kinetic communicator exercise device. Medicine and Science in Sports and Exercise, 18(1), 44-49.

Favier, R., Constable, S., Chen, M. & Holloszy, J. (1986). Endurance exercise training reduces lactate production. Journal of Applied Physiology, 61(3), 885-889.

Gollnick, P., Armstrong, R., Saltin, B., Saubert, C., Sembrowich, W. & Shepherd, R. (1973). Effect of training on enzyme activity and fiber composition of human skeletal muscle. Journal of Applied Physiology, 34(1), 107-111.

Gollnick, P., Armstrong, R., Saubert, C., Piehl, K. & Saltin, B. (1972). Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. Journal of Applied Physiology, 33, 312-319.

Green, H., Thomson, J., Daub, W., Houston, M. & Ranney, D. (1979). Fiber composition, fiber size and enzyme activities in vastus lateralis of elite athletes involved in high intensity exercise. European Journal of Applied Physiology, 41, 109-117.

Gregor, R., Edgerton, V., Perrine, J., Camption, D. & DeBus, C. (1979). Torque-velocity relationships and muscle fiber composition in elite female athletes. Journal of Applied Physiology, 47, 388-392.

Hagberg, J., Hickson, R., Ehsani, A. & Holloszy, J. (1980). Faster adjustment to and recovery from submaximal exercise in the trained state. Journal of Applied Physiology, 48(2), 218-224.

Hagerman, F., Connors, M., Gault, J., Hagerman, G. & Polinski, W. (1978). Energy expenditure during simulated rowing. Journal of Applied Physiology, 45(1), 87-93.

Hagerman, F. & Staron, R. (1983). Seasonal variations amoung physiological variables in elite oarsmen. Canadian Journal of Sport Sciences, 8(3), 143-148.

Hakkinen, K. & Komi, P. (1983). Electromyographic changes during strength training and detraining. Medicine and Science in Sports and Exercise, 15(6), 455-460.

Hardman, A., William, C. & Wootton, S. (1986). The influence of short-term oxygen uptake, submaximal endurance and the ability to perform brief, maximal exercise. Journal of Sport Science, 4, 109-116.

Henriksson, J, & Reitman, J. (1977). Time course of changes in human skeletal muscle succinate dehydrogenase and cytochrome oxidase activities and maximal oxygen uptake with physical activity and inactivity. Acta Physiologica Scandinavica, 99, 91-97.

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology, 45, 255-263.

Hickson, R., Bomze, H. & Holloszy, J. (1978). Faster adjustment of O_2 uptake to the energy requirement of exercise in the trained state. Journal of Applied Physiology, 44(6), 877-881.

Hickson, R., Rennie, M., Conlee, R., Winder, W. & Holloszy, J. (1977). Effects of increased plasma fatty acids on glycogen utilization and endurance. Journal of Applied Physiology, 43(5), 829-833.

Hill, A. V. (1970). First and last experiments in muscle mechanics. Cambridge University Press: London.

Hislop, H. & Perrine, J. (1967). The isokinetic concept of exercise. Physical Therapy, 47, 114-117.

Holloszy, J. & Coyle, E. (1984). Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. Journal of Applied Physiology, 56(4), 831-838.

Houston, M., Bentzen, H. & Larsen, H. (1979). Interrelationships between skeletal muscle adaptations and performance as studied by detraining and retraining. Acta Physiologica Scandinavica, 105, 163-170.

Houston, M., Froese, E., Valeriote, P., Green, H., Ranney, D. (1983). Muscle performance, morphology and metabolic capacity during strength training and detraining: A one leg model. European Journal of Applied Physiology, 51, 25-35.

Howald, H. (1982). Training-induced morphological and functional changes in skeletal muscle. International Journal of Sports Medicine, 3, 1-12.

Hunter, G., Demment, R. & Miller, D. (1987). Development of strength and maximal oxygen uptake during simultaneous training for strength and endurance. The Journal of Sports Medicine and Physical Fitness, 27(3), 269-275.

Hurley, B., Hagberg, J., Allen, W., Seals, S., Young, J., Cuddihee, R. & Holloszy, J. (1984). Effect of training on blood lactate levels during submaximal exercise. Journal of Applied Physiology, 56(5), 1260-1264.

Hurley, B., Nemeth, P., Martin, W., Hagberg, J., Dalsky, G., Holloszy, J. (1986). Muscle triglyceride utilization during exercise: effect of training. Journal of Applied Physiology, 60(2), 562-567.

Ikai, M. & Steinhaus A. (1961). Some factors modifying the expression of human strength. Journal of Applied Physiology, 16, 157-163.

Ivy, J., Withers, R., Brose, G., Maxwell, B. & Costill, D. (1981). Isokinetic contractile properties of the quadraceps with relation to fiber type. European Journal of Applied Physiology, 47, 247-2551

Jacobs, I., Sale, D., & MacDougall, J. (1987). Combined strength and endurance training effects on muscle enzymatic and histochemical characteristics. (Abstract). Medicine and Science in Sports and Exercise, 19(2), S88.

Jansson, E. & Kaijser, L. (1977). Muscle adaptation to extreme endurance training in man. Acta Physiologica Scandinavica, 100, 315-324.

Kanehisa, H. & Miyashita M. (1983a). Specificity of velocity in strength training. European Journal of Applied Physiology, 52, 104-106.

Kanehisa, H. & Miyashita M. (1983b). Effect of isometric muscle training on static and dynamic power. European Journal of Applied Physiology, 50, 354-371.

Karlsson, J., Sjoden, B., Thorstensson, A., Hulten, B. & Frith, K. (1975). LDH isozymes in skeletal muscles of endurance and strength trained athletes. Acta Physiologica Scandinavica, 93,150-156.

Katch, F., Stanley, S. & Freedson, P. (1982). Biological variability in maximum aerobic power. Medicine and Science in Sports and Exercise, 14, 21-25.

Klausen, K., Andersen, L. & Pelle, I. (1981). Adaptive changes in work capacity, skeletal muscle capillarization and enzyme levels during training and detraining. Acta Physiologica Scandinavica, 113, 9-16.

Knuttgen, H. & Kraemer, W. (1987). Terminology and measurement in exercise performance. Journal of Applied Sport Science Research, 1, 1-10.

Komi, P., Viitasalo, J., Rauramaa, R. & Vihko V. (1978). Effect of isometric strength training of mechanical, electrical and metabolic aspects of muscle function. European Journal of Applied Physiology, 40, 45-55.

Krotkiewski, M., Aniansson, A., Grimby, G., Bjorntorp, P. & Sjostrom, L. (1979). The effect of unilateral isokinetic strength training on local adipose and muscle tissue morphology, thickness and enzymes. European Journal of Applied Physiology, 42, 271-281.

Lesmes, G., Costill, D., Coyle, E. & Fink, W. (1978). Muscle strength and power changes during maximal isokinetic training. Medicine and Science in Sports, 10(4), 266-269.

Luthi, J., Howald, H., Claassen, H., Rosler, K., Vock, P. & Hoppeler, H. (1986). Structural changes in skeletal muscle tissue with heavy-resistance exercise. International Journal of Sports Medicine, 7, 123-127.

Mahler, D., Parker, H. & Andresen, D. (1985). Physiologic changes in rowing performance associated with training in collegiate women rowers. International Journal of Sports Medicine, 6(4), 229-233.

MacDougall, J. (1977). The anaerobic threshold: Its significance for the endurance athlete. Canadian Journal of Applied Sport Sciences, 2, 137-140.

MacDougall, J. (1986). Morphological changes in human skeletal muscle following strength training and immobilization. In Jones, N., McCartney, N. & McComas, A. (Eds.), Human muscle power. Human Kinetic Publishers: Champaign.

MacDougall, J., Elder, G., Sale, D., Moroz, J. & Sutton, J. (1980). Effects of strength training and immobilization on human muscle fibers. European Journal of Physiology, 43, 25-34.

MacDougall, J., Sale, D., Alway, S. & Sutton, J. (1982). Muscle ultrastructural characteristics of elite powerlifters and bodybuilders, European Journal of Applied Physiology, 48, 117-126.

MacDougall, J., Sale, D., Jacobs, I., Garner, S., Moroz, D. & Dittmer, D. (1987). Concurrent strength and endurance training do not impede gains in $\dot{V}O_2max$. (Abstract). Medicine and Science in Sports and Exercise, 19(2), S87.

MacDougall, J., Sale, D., Moroz, J., Elder, G., Sutton, J. & Howald, H. (1979). Mitochondrial volume density in human skeletal muscle following heavy resistance training. Medicine and Science in Sports, 11, 164-166.

MacDougall, J., Ward, G., Sale, D. & Sutton, J. (1977). Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. Journal of Applied Physiology, 43(4), 700-703.

Martin, T. (1987). Predictable adaptations by skeletal muscle mitochondria to different exercise training workloads. Comparative Biochemistry and Physiology, 88B(1), 273-276.

Martindale, W. & Robertson, D. (1984). Mechanical energy in sculling and in rowing an ergometer. Canadian Journal of Applied Sports Sciences, 9(3), 153-163.

McLellan, T. & Skinner, J. (1985). The use of the aerobic threshold as a basis for training. Canadian Journal of Applied Sport Sciences, 6(4), 197-201.

Milner-Brown, H., Stein, R. & Lee, R. (1975). Synchronization of human motor units: Possible roles of exercise and supraspinal reflexes. Electroencephalography and Clinical Neurophysiology, 38, 245-254.

Moffroid, M. & Whipple, R. (1970). Specificity of speed of exercise. Physical Therapy, 50(12), 1692-1700.

Moore, R., Thacker, E., Kelley, G., Musch, T., Sinoway, L., Foster, V. & Dickinson, A. (1987). Effect of training/detraining on submaximal exercise responses in humans. Journal of Applied Physiology, 63(5), 1719-1724.

Moritani, T. & DeVries H. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115-130.

Nelson, A., Conlee, R., Arnall, D., Loy, S. & Silvester, L. (1984). Adaptations to simultaneous training for strength and endurance. (Abstract). Medicine and Science in Sports and Exercise, 16, 184.

Nobbs, L. & Rhodes, E. (1986). The effect of electrical stimulation and isokinetic exercise on muscular power of the quadraceps femoris. Journal of Orthopeadic and Sports Physical Therapy, 8(5), 260-268.

Nordesjo, L. (1974). The effect of quantified training on the capacity for short and prolonged work. Acta Physiologica Scandinavica Supplement, 405.

Perrine, J. & Edgerton, V. (1978). Muscle force-velocity and power-velocity relationships under isokinetic loading. Medicine and Science in Sports, 10(3), 159-166.

Perry, S. (1974). Calcium ions and the function of contractile proteins of muscle. Biochemistry Society Symposium, 39, 115-132.

Perry, B. & Bridges, C. (1973). Computerized transverse axial scanning (tomography): Part 3. Radiation dose considerations. British Journal of Radiology, 46, 1048-1051.

Petersen, S., Miller, G., Quinney, H. A. & Wenger, H. A. (1988). The influence of high-velocity resistance circuit training on aerobic power. Journal of Orthopeadic and Sports Physical Therapy, 9(10), 339-344.

Petersen, S., Miller, G., Wenger, H. & Quinney, H. (1984). The aquisition of muscular strength: the influence of training velocity and initial VO_2max. Canadian Journal of Applied Sport Science, 9(4): 176-180.

Rasch, P. & Morehouse, L. (1957). Effect of static and dynamic exercises on muscular strength and hypertrophy. Journal of Applied Physiology, 11(1): 29-34.

Riedy, M., Moore, R. & Gollnick, P. (1985). Adaptive response of hypertrophied muscle to endurance training. Journal of Applied Physiology, 59(1), 127-131.

Rowell, L. (1980). What signals govern the cardiovascular responses to exercise? Medicine and Science in Sports and Exercise, 12(5), 307-315.

Rutherford, O. & Jones D. (1986). The role of learning and coordination in strength training. European Journal of Applied Physiology, 55, 100-105.

Sale, D. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5), S135-S145.

Sale, D. (1987). Influence of exercise and training on motor unit activation. Exercise and Sport Sciences Reviews, 15, 95-151.

Sale, D. (1986). Neural adaptation in strength and power training, in Jones, N., McCartney, N. & McComas, A. (eds.), Human Muscle Power. Champaign, Illinois, Human Kinetics Publishers Inc., pp 289-305.

Sale, D. & MacDougall, J. (1981). Specificity in strength training: A review for the coach and athlete. Canadian Journal of Applied Sport Sciences, 6, 87-92.

Sale, D., McComas, A., MacDougall, J. & Upton, A. (1982). Neuromuscular adaptation in human thenar muscles following strength training and immobilization. Journal of Applied Physiology, 53, 419-424.

Sale, D., Upton, A., McComas, A., MacDougall, J. (1983). Neuromuscular function in weight-trainers. Experimental Neurology, 82, 521-531.

Saltin, B., Henriksson, E., Nygaard, E., Andersen, P. & Jansson, E. (1977). Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. Annals New York Academy of Sciences, 301, 3-29.

Saltin, B. & Rowell, L. (1980). Functional adaptations to physical activity and inactivity. Federation Proceedings, 39, 1506-1513.

Schantz, P, Henriksson, J. & Jansson, E. (1983). Adaptations of human skeletal muscle to endurance training of long duration. Clinical Physiology, 3, 141-151.

Secher, N. (1983). The physiology of rowing. Journal of Sport Sciences, 1, 23-63.

Shapiro, L. (1987). Left ventricular hypertrophy in athletes in relation to the type of sport. Sports Medicine, 4, 239-244.

Sigma Chmeical Company (1981). The quantitative determination of pyruvic acid and lactic acid. Sigma Technical Bulletin No. 826-UV. Sigma Chemical Company: St. Louis.

Smith, M. & Melton, P. (1981). Isokinetic versus isotonic variable-resistance training. American Journal of Sports Medicine, 9(4), 275-279.

Stone, M. (1988). Implications for connective tissue and bone alterations resulting from resistance exercise training. Medicine and Science in Sports and Exercise, 20(5), S162-S168.

Sprynarova, S., Bass, A., Mackova, E., Vondra, K., Vitek, V., Teisinger, J. & Malkovska, M. (1980). Adaptations of man to extreme endurance training. European Journal of Applied Physiology, 44, 17-23.

Tesch, P. (1988). Skeletal muscle adaptations consequent to long-term heavy resistance exercise. Medicine and Science in Sports and Exercise, 20(5), S132-S134.

Tesch, P. (1987). Acute and long-term metabolic changes consequent to heavy-resistance exercise. Medicine and Sport Science, 26, 67-89.

Tesch, P. & Karlsson, J. (1985). Muscle fiber types and size in trained and untrained muscles of elite athletes. Journal of Applied Physiology, 59(6), 1716-1720.

Tesch, P., Komi, P. & Hakkinen, K. (1987). Enzymatic adaptations to long-term strength training. International Journal of Sports Medicine, 8, 66-69.

Thoden, J., Wilson, B. & MacDougall, J. (1982). Testing Aerobic Power. In MacDougall, J., Wenger, H. & Green, H. (Eds), Physiological testing of the elite athlete. Mutual Press Limited: Ottawa.

Thorstensson, A. (1977). Observations on strength training and detraining. Acta Physiologica Scandinavica, 100: 491-493.

Thorstensson, A., Hulten, B., Von Dobeln, W. & Karlsson, J. (1976). Effect of strength training on enzyme activities and fibre characteristics in human skeletal muscle. Acta Physiologica Scandinavica, 96: 392-398.

Thorstensson, A., Larsson, L., Tesch, P. & Karlsson, J. (1977). Muscle strength and fiber composition in athletes and sedentary men. Medicine and Science in Sports, 9(1), 26-30.

Volkov, N., Shirkovets, E. & Borilkovich, V. (1975). Assessment of aerobic capacity of athletes in treadmill running tests. European Journal of Applied Physiology, 34, 121-130.

Watkins, M. & Harris, B. (1983). Evaluation of isokinetic muscle performance. Clinics in Sports Medicine, 2(1), 37-53.

Wessel, J., Gray, G., Luongo, F. & Isherwood, L. (1988). The reliability of work measurements recorded during concentric and eccentric contractions of the knee extensors. Physiotherapy Canada, In Press.

Wilke, D. (1950). The relation between force and velocity to human muscle. Journal of Physiology (London), 110, 249-280.

Wyndham, C., Strydom, N., Van Rensburg, A. & Benade, A. (1969). Physiological requirements for world-class performances in endurance running. South African Medical Journal, 43(9), 996-1002.

APPENDIX B

SPORT PHYSIOLOGY LAB
DEPARTMENT OF PHYSICAL EDUCATION AND SPORT STUDIES
UNIVERSITY OF ALBERTA

INFORMED CONSENT FOR PHYSIOLOGICAL ASSESSMENTS

The following physiological assessments (indicated by a check unless otherwise stated) will be conducted by qualified personnel as a part of a personal fitness appraisal and/or research project:

A). **Physiological Responses to a Submaximal Workload**

Ergometer:

a). heart rate[1] ( ) c). other ( )

b). metabolic responses[2] ( ) --------------------

B). **Maximal Oxygen Consumption ($\dot{V}O_{2max}$)**

Ergometer:

a). heart rate ( ) c). other ( )

b). metabolic responses ( ) --------------------

C). **Anaerobic Threshold (Ventilation and/or Lactate Threshold)**

Ergometer:

a). heart rate ( ) c). blood lactate ( )

b). metabolic responses ( ) d). other ( )

D). Isokinetic Strength Assessment at Various Angular Velocities

Dynamometer:

a). peak torque ( )

b). work ( )

c). muscular endurance ( )

d). joint(s)

e). number of contractions

f). angular velocities

E). Anaerobic Power and/or Capacity

Ergometer:

a). power output ( )

b). total rpms ( )

c). blood lactate ( )

d). other ( )

\-------------------

F). Body Conposition

a). height/weight ( )

b). skinfolds ( )

c). body densiometry

G). Flexibility

a). sit and reach ( )

b). other

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H). Muscular Endurance

a). situps ( )

b). pushups ( )

b). other ( )

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I). Blood Chemistry Analyses[3]

a). hemoglobin ( )

b). hematocrit ( )

c). lactate ( )

c). glucose ( )

d). other ( )

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1. Heart rate will be determined with either an ECG ( ) or a sport tester heart rate monitor ( ).

2. Metabolic responses will be assessed using open circuit spirometry with analyses of expired air by a Beckman Metabolic Measurement Cart (MMC).

3). A blood sample will be taken from an antecubital vein (.), a finger tip prick ( ), or from an indwelling catheter ( ) by a qualified lab technician or IV nurse.

Research Project

The proposed research project involves the physiological assessments selected above as well as computerized tomography (CT) scans of the thigh to assess cross-sectional area of the quadraceps (hypertrophy). This scan constitutes only a 1 cm cross-sectional X-ray of the mid thigh at a level normally used for diagnostic examination and does not constitute a health concern. The CT scan will be conducted at the Cross Cancer Institute (U. of A.) by a qualified lab technician. Only 4 CT scans will be taken during the study and the physiological assessments will be repeated periodically.

Training

Resistance training will be conducted on 12 stations of variable resistance hydraulic equipment (Hydra-Fitness). The subjects will progress 3 circuits of either high or low velocity training completing 2 sets at each station. The work to rest ratio will be 1:1. Subjects will be required to perform maximally during each set of exercise. Each session will require approximately one hour and fifteen minutes.

Endurance training will be continuous exercise on rowing ergometers (Concept II). The intensity will be moderate, approximately 75% of the individual $\dot{V}O_2max$. Training duration will progress to 60 minutes. All subjects will use heart rate monitors to maintain the desired training intensity. Training will require about 1 hour.

All training will be supervised and each subject will be required to record daily training information.

Agreement

The above tests will be conducted by qualified personnel under controlled laboratory conditions. All results are confidential and will be used only as group data in research unless specific approval has been given by each individual. While injury or illness is unlikely during testing, lab personnel are trained for standard emergency procedures. The intensity of the maximal tests require strenuous effort by each subject but the exercise will not exceed those experienced during performance in sport. Subects may discontinue any of the testing on their own volition.

CONSENT

I have read the above and agree to participate in the physiological assessments ( ) and/or research project ( ) at my own risk. I realize that I may expect a thorough explanation and demonstration of any procedures and that I am a volunteer and can terminate participation at any time of my own volition.

Having voluntarily assumed participation and the risks involved, I hereby disclaim and release the University of Alberta, its agents or employees, including all personnel involved with the physiological testing and/or research project from any liability that might arise as a result of my participation as a subject.

Name: _______________________________________ Date: ___________

Address: ____

____

Signature: ________________________________

APPENDIX C

Appendix C. Unadjusted intraclass correlation coefficients (ICC) for maximal oxygen consumption ($\dot{V}O_2max$), maximal heart rate (HRmax), submaximal heart rate (HRsub), submaximal blood lactate (BLa), submaximal oxygen consumption ($\dot{V}O_2sub$) and knee extension peak torque (PT) and total work (TW) during four maximal knee extensions at 1.05 rad · s^{-1}.

Variable	ICC
$\dot{V}O_2max$ (l · min^{-1})	.965
$\dot{V}O_2max$ (ml · kg^{-1} · min^{-1})	.960
HRmax (beats · min^{-1})	.994
HRsub (beats · min^{-1})	.891
BLa (mmol · l^{-1})	.910
$\dot{V}O_{2sub}$ (l · min^{-1})	.998
PT at 1.05 rad · s^{-1} (N·m)	.983
TW at 1.05 rad · s^{-1} (J)	.980

APPENDIX D

Appendix D Description

A comparison of knee extension peak torque and total work at 1.05 rad · s^{-1} (Figure 1 and 2) and cross sectional area (Figure 3) of the quadriceps femoris muscle between a group of oarsmen (n=14) who performed concurrent endurance and low velocity resistance training (group ES) and a group of active subjects (n=15) who peformed the identical low velocity resistance training program at the same time but without endurance training (group S). Data for group S based on unpublished observations by S. Petersen. Methodology was described in paper 3 (Chapter 4).

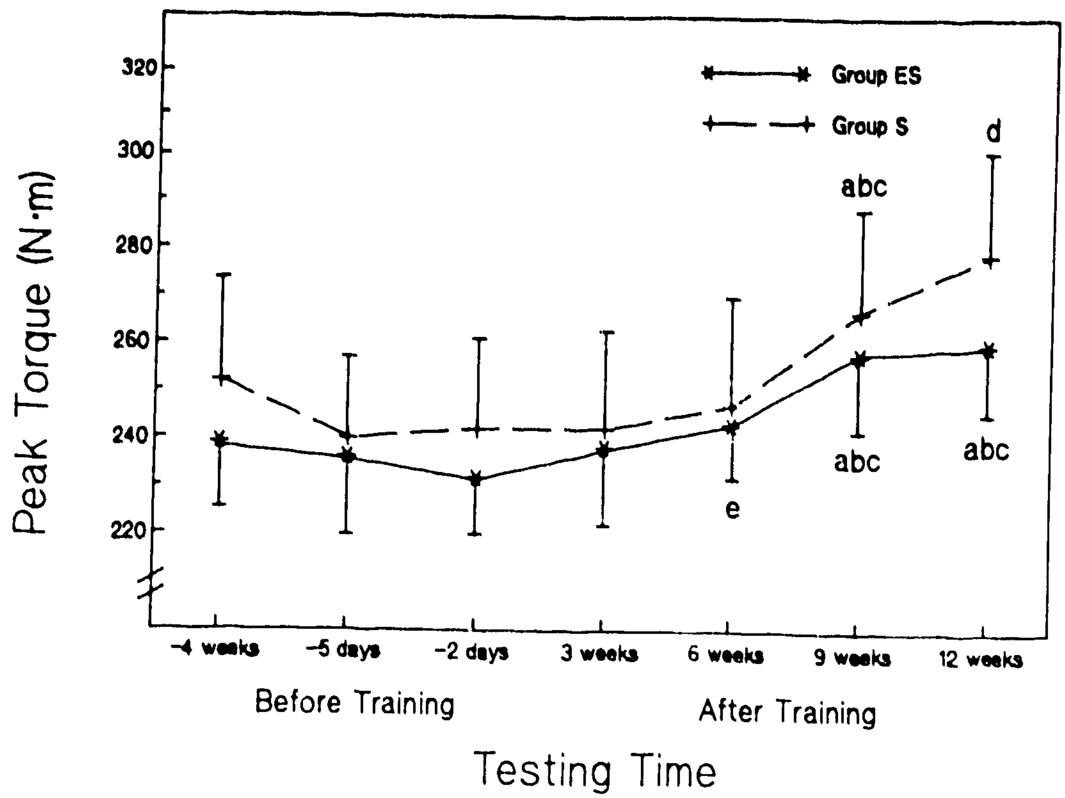

Figure 1. Knee extension peak torque at 1.05 rad · s^{-1} before, during and after concurrent endurance and low velocity resistance training (group ES) and low velocity resistance training only (group S).

Values are means (SE).

a = significantly different from before training, $p < 0.05$.

b = significantly different from week 3, $p < 0.05$.

c = significantly different from week 6, $p < 0.05$.

d = significantly different from all other scores, $p < 0.05$.

e = significantly different from -2 days, $p < 0.05$.

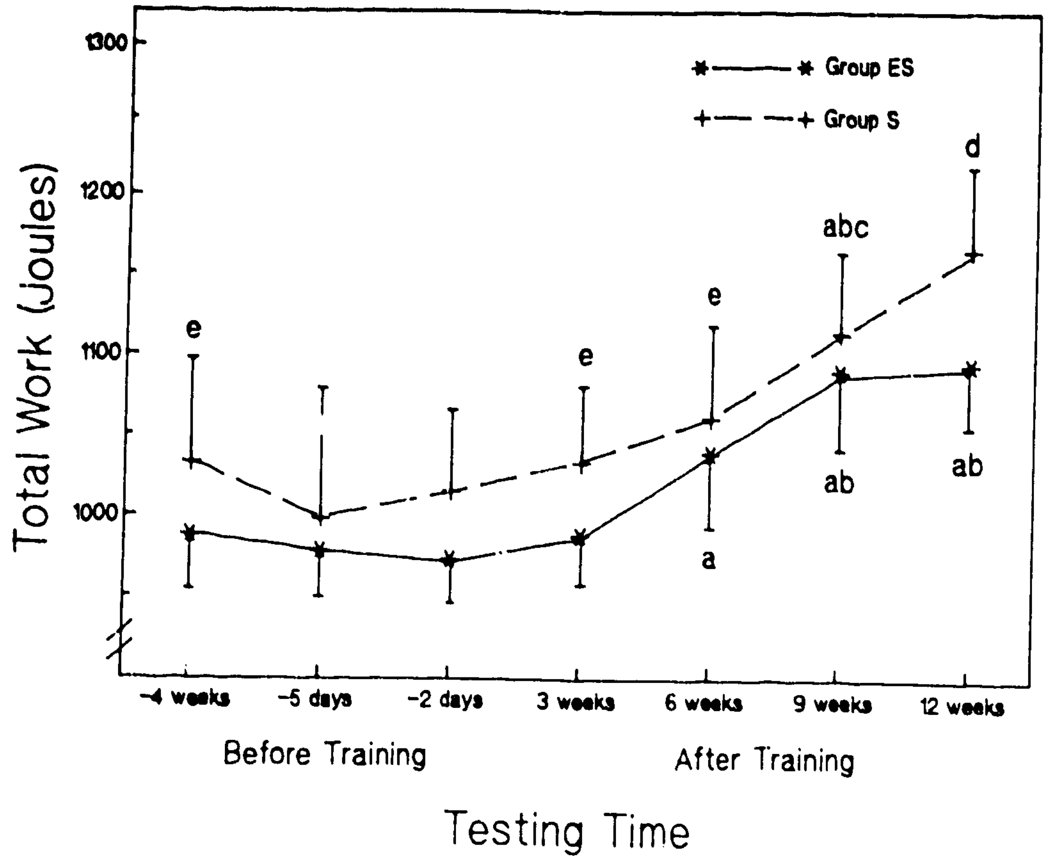

Figure 2. Total work during four knee extensions at 1.05 rad · s^{-1} before, during and after concurrent endurance and low velocity resistance training (group ES) and low velocity resistance training only (group S).

Values are means (SE).

a = significantly different from before training, $p < 0.05$.

b = significantly different from week 3, $p < 0.05$.

c = significantly different from week 6, $p < 0.05$.

d = significantly different from all other scores, $p < 0.05$.

e = significantly different from -5 days, $p < 0.05$.

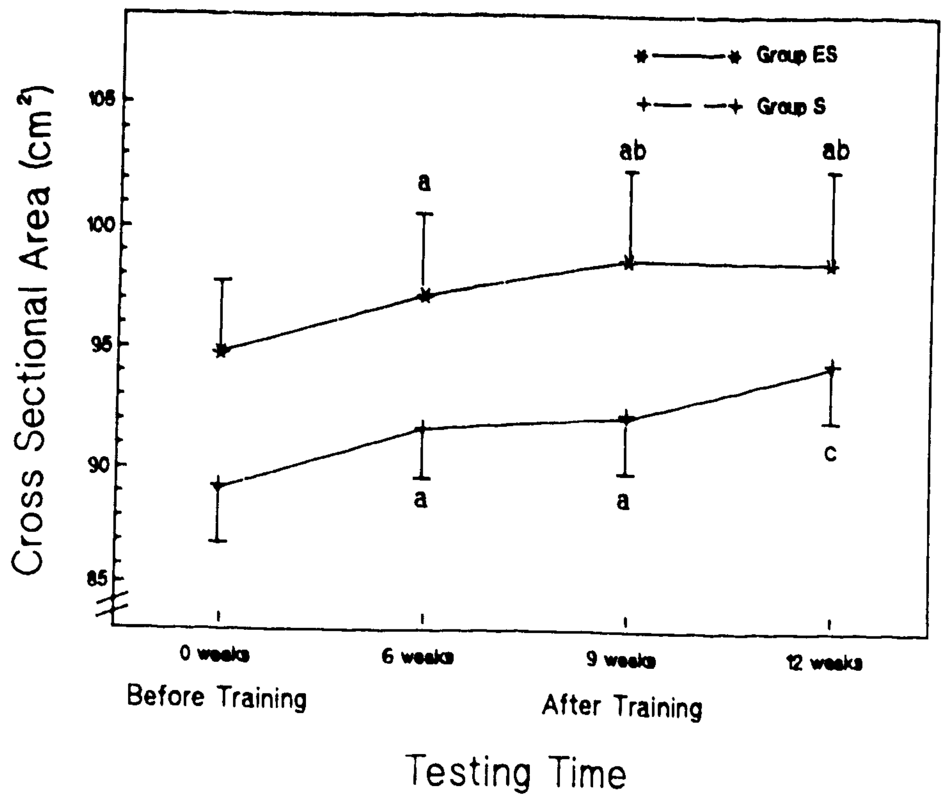

Figure 3. Cross sectional area of the quadriceps femoris muscle before, during and after concurrent endurance and low velocity resistance training (group ES) and low velocity resistance training only (group S).

Values are means (SE).

a = significantly different from before training, $p < 0.05$.

b = significantly different from week 6, $p < 0.05$.

c = significantly different from all other scores, $p < 0.05$.

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PUBLICATIONS, ABSTRACTS AND PROCEEDINGS

1). Wenger, H. A. & Bell, G. J. (1986). The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. **Sports Medicine**, 3(5), 346-356.

2). Howe, B. L. & Bell, G. J. (1986). Mood states and motivation of triathletes. In Watkins, J., Reilly, T. & Burwitz, L. (Eds.), **Sport Science: Proceedings of the VIII Commonwealth and International Conference on Sport, Physical Education, Dance, Recreation and Health**, 273-278.

3). Bell, G. J. & Wenger, H. A. (1986). The effect of sprint training on intramuscular pH, buffering capacity and lactate. Abstract. **Canadian Journal of Applied Sport Sciences**, 11(3), 3P.

4). Quinney, H. A., Petersen, S., Drake, C., Tubman, L. A., Bell, G. J. & Wenger, H. A. (1987). The effects of a power training mini-cycle for ice hockey. Abstract. **Canadian Journal of Sport Sciences**, 12(3), 19P.

5). Bell, G. J. & Howe, B. L. (1988). Mood state profiles and motivations of triathletes. **Journal of Sport Behavior**, 11(2), 66-77.

6). Bell, G. J., Neary, J. P. & Wenger, H. A. (1988). The influence of one-legged training on cardiorespiratory fitness. **Journal of Orthopeadic and Sports Physical Therapy**, 10(1), 8-11.

7). Bell, G. J. & Wenger, H. A. (1988). The effect of one-legged sprint training on intramuscular pH and nonbicarbonate buffering capacity. **European Journal of Applied Physiology**, 58, 158-164.

8). Bell, G. J., Petersen, S. R., Quinney, H. A. & Wenger, H. A. (1988). Sequencing of endurance and high velocity strength training. **Canadian Journal of Sport Science**, 13(4), 214-219.

9). Bell, G. J., Snydmiller, G. D., Neary, J. P. & Quinney, H. A. (1989). The effect of high and low velocity resistance training on anaerobic power output in cyclists. **The Journal of Human Movement Studies**, In Press.

10). Bell, G. J., Petersen, S. R., Quinney, H. A. & Wenger, H. A. (1989). The effect of velocity-specific strength training on peak torque and anaerobic rowing power. **Journal of Sports Sciences**, In Press.

11). Bell, G. J., Petersen, S. R., Quinney, H. A., Wessel, J. & Bagnall, K. Physiological adaptations to endurance and low velocity resistance training performed in a sequence. Submitted to **Medicine and Science in Sports and Exercise.**

12). Bell, G. J., Snydmiller, G. D., Neary, J. P. & Quinney. Effects of two velocities of resistance training on knee and elbow extensors and flexors. Submitted to **The Journal of Orthopeadic and Sports Physical Therapy.**

13). Neary, J. P., Bell, G. J., Snydmiller, G. D. & Quinney, H. A. Creatine phosphokinase alterations during high intensity resistance training. Submitted to the **Australian Journal of Sports Medicine.**

14). Bell, G. J., Petersen, S., MacLean, I., Reid, D. & Quinney, H. A. The effect of high velocity resistance training on peak torque, cross sectional area and myofibrillar ATPase activity. Submitted to **The Journal of Sports Medicine and Physical Fitness.**

15). Bell, G. J., Petersen, S., Wessel, J., Bagnall, K. & Quinney, H. A. Physiological adaptations to concurrent endurance and low velocity resistance training. Submitted to the **International Journal of Sports Medicine.**