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Virginia Commonwealth University
School of Basic Health Sciences

This is to certify that the dissertation prepared by Thomas Philip Mayhew entitled "The effects of concentric and eccentric contractions performed at equal power levels on skeletal muscle fiber hypertrophy" has been approved by his committee as satisfactory completion of the dissertation requirement for the degree of Doctor of Philosophy.

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THE EFFECTS OF CONCENTRIC AND ECCENTRIC CONTRACTIONS PERFORMED AT EQUAL POWER LEVELS ON SKELETAL MUSCLE FIBER HYPERTROPHY

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Anatomy
at Virginia Commonwealth University.

By

Thomas Philip Mayhew
B.S. State University of New York at Buffalo, 1979
B.S. Washington University, 1983
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December, 1991

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Acknowledgements

This dissertation reflects the contributions of a number of outstanding people within the university community. To those faculty, staff, and students who helped me complete this project, but whose names do not appear on this page, I give my heartfelt thanks for your help, patience, and support over the last several years.

I would like to express my sincere appreciation to Dr. Jules Rothstein for your guidance, friendship, and moral support throughout my graduate education. Your patience, encouragement, and knowledge in the field of muscle biology contributed greatly not only to the final results of this project, but also to the growth of my mind.

I would like to thank my committee members Dr. Steve Goldberg, Dr. Ross McClung, Dr. Otto Payton, Dr. Jim Poland, and Dr. Robert Lamb. I would like to give special thanks to Dr. Steve Goldberg for taking over as my advisor when Jules left the university. I would also like to give special thanks to Dr. Robert Lamb for his financial and moral support over the last several years.

I would like to thank my colleagues in the Department of Physical Therapy for their support and friendship; especially, Sheryl Finucane and Dan Riddle for their long conversations which kept me on track.

Thanks also to the twenty students who put up with numerous biopsies and a difficult training program to serve, without compensation, as my subjects. I truly could not have begun this project without you.

Above all, I would like to thank my wife and best friend, Jill Mayhew for her continuous support and encouragement over the last several years. This dissertation is dedicated, with my sincere thanks, to Jill because I could not have completed it without her support.

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LIST OF ABBREVIATIONS AND SYMBOLS

acc	acceleration
ATP	adenosine triphosphate
ATPase	adenosine triphosphatase
ANOVA	analysis of variance
CRT	cathode ray tube
C	celsius
r^2	coefficient of determination
cc	cubic centimeters
dec	deceleration
°	degree(s)
df	degrees of freedom
°/sec	degrees per second
°/V	degrees per volt
DOMS	delayed-onset muscle soreness
Hz	hertz
init. force	initial force
ICC	intraclass correlation coefficient
kg	kilogram(s)
MS	mean squares
µm	micrometer(s)
µV	microvolt(s)
N	newton(s)
N/V	newtons per volt
RM	one repetition maximum
%	percent
±	plus or minus
sec	second(s)
μm^2	square micrometers
SD	standard deviation
SG	strain gauge
SS	sum of the squares
ver.	version
vs.	versus
V	volt(s)

THE EFFECTS OF CONCENTRIC AND ECCENTRIC CONTRACTIONS PERFORMED AT EQUAL POWER LEVELS ON SKELETAL MUSCLE FIBER HYPERTROPHY

ABSTRACT

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Anatomy at Virginia Commonwealth University.

Thomas P. Mayhew, Ph.D.

Medical College of Virginia, Virginia Commonwealth University, 1991

There are no data available as to whether training with eccentric contractions are more effective than concentric contractions for producing skeletal muscle fiber hypertrophy. To better understand the effects of training with different contraction types two related studies were performed.

In the first study a device which is frequently used by clinicians for concentric and eccentric exercise, the Kin-Com^R, was tested for accuracy and reliability. The measurements obtained from the force, angle, and speed transducers of this device were found to be accurate and reliable between days.

The purpose of the second study was to determine if there was a difference in the percent change of fiber area in the vastus lateralis muscle as a result of concentric and eccentric exercise at equal power levels. Twenty normal subjects were randomly assigned to two groups. Both groups exercised three times per week for four weeks on the Kin-Com dynamometer. One group performed concentric contractions of their right quadriceps femoris muscle at an intensity of 90% of their maximal concentric power through a range of 75° of knee extension. The other group performed eccentric contractions at the same relative power level. Needle muscle biopsies were obtained from the vastus lateralis muscle before and after the exercise program. Muscle fiber type differentiation was performed using a myosin adenosine triphosphatase stain at an alkaline preincubation. The percent change in fiber area was determined for each fiber type for each subject and a one-way ANOVA was used to analyze the data. Our results showed that the type II fibers of the concentric group exhibited a greater percent increase in area as compared to the eccentric group. The percent change in isometric torque was determined for each subject and a one-way ANOVA was performed on the data. The results showed that the concentric group increased maximal isometric torque production more than the eccentric group. Our results indicate that when exercising at the same relative power level a subject performing concentric contractions will 1) show greater muscle hypertrophy and, 2) improve in isometric torque production more than a subject training with eccentric contractions.

PART 1

Performance Characteristics of the Kin-Com Dynamometer

This chapter is to be submitted for publication in *Physical Therapy*, the professional journal of the American Physical Therapy Association.

Performance Characteristics of the Kin-Com Dynamometer

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ABSTRACT

The purpose of this study was to assess the performance characteristics of the of the Kin-Com[R] dynamometer under controlled conditions. Measurements obtained from the Kin-Com[R], and simultaneous measurements obtained from an external recording system, were compared with known weights, angles, and speeds. Reliability within and between days was evaluated with an intraclass correlation coefficient (ICC) by performing each test protocol twice on the same day and on two successive days. The strength of the linear relationships between the variables tested was analyzed using a coefficient of determination (r^2). In all conditions the r^2 for the force measurements was above .99. The agreement (ICC) between days for all force conditions was also above .99. In all conditions the r^2 for the angle measurements was above .99. The agreement (ICC) between days for all conditions was 1.00. The r^2 for the speed measurements was above .99 for all conditions. When various selected aspects of the speed measurements were considered the r^2 values were somewhat lower but never lower than .83. It was discovered, however, that use of any acceleration and deceleration mode other than "high" resulted in a loss of excursion of the lever arm. Our results indicate that the static measurements of force and angle that are necessary for use in the gravity correction procedure are accurate and reliable between days. Also, the Kin-Com's[R] control system for lever arm speed is accurate and reliable.

INTRODUCTION

Devices designed to measure forces generated by muscles are commonly used in physical therapy clinics. These devices range from simple hand-held instruments to more complex dynamometers which can measure the torque produced during limb movements (Mayhew & Rothstein, 1985). In the last two decades muscle testing devices have been developed which can all be classified as some form of electromechanical dynamometer. These dynamometers can control the speed of limb movement while measuring muscularly generated force or torque. Electromechanical dynamometers are currently used by clinicians and researchers for a variety of purposes related to muscular testing and exercise.

Little data, however, are available concerning the accuracy and reliability of the measurements obtained with these devices. Researchers and clinicians who take measurements are responsible for establishing the reliability of these measurements. A logical place to begin evaluation of the measurements obtained with an electromechanical dynamometer is to test the accuracy and reliability of each of the transducers (e.g., strain gauges, tachometer, and potentiometer). A study by Farrell and

Richards (1986) described one possible method for performing such an evaluation. They examined the reliability and validity of the force, angle, and speed transducers of the Kin-Com[R1]. Our study represents an example of another method for the systematic analysis of the accuracy and reliability of the Kin-Com's[R] transducers.

The Kin-Com[R], which is currently used for the measurement of forces produced by muscular contractions, is a computer controlled electromechanical dynamometer. The device provides resistance during isokinetic (constant speed) movement, and isometric and isotonic muscle contractions. Investigators examining a variety of questions related to the measurement and improvement of muscle force have also used the device (Hageman, Gillaspie, & Hill, 1988; Hanten & Ramberg, 1988; Hart, Miller, & Stauber, 1985; Jensen & Di Fabio, 1989).

One of the most common uses of the Kin-Com[R] is isokinetic testing and exercise (Farrell & Richards, 1986). Reviewers examining the literature related to "isokinetic dynamometers" have noted a number of problems associated with the performance characteristics of these devices as well as the measurements obtained with them (Mayhew & Rothstein, 1985; Rothstein, Lamb, & Mayhew, 1987). The majority of these studies have focused on another widely

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[1] Chattecx Corp., 101 Memorial Drive, PO Box 4287, Chattanooga, TN 37405

used electromechanical dynamometer, the Cybex II^R[2]. Control of lever arm speed is an essential characteristic of a device that must maintain a constant speed while resisting the movement of a subject's limb. Evaluations of the Cybex II^R dynamometer have demonstrated that this control can be a problem (Sapega, Nicholas, Sokolow, & Saraniti, 1982; Thorstensson, Brimby, & Karlsson, 1976).

In this study we evaluated the relationship between set speeds and actual lever arm speeds of the Kin-Com^R without a subject applying force to the lever arm. We felt that this was a necessary first step in evaluating the performance characteristics of this device. Options were available in the software to control acceleration and deceleration of the lever arm to and from constant speed, as well as the direction of lever arm movement. Therefore, we felt that testing a representative number of lever arm speeds in all possible combinations of acceleration and deceleration in both the upward and downward directions was essential to understanding the performance characteristics of the device. We believe that this information is important for both researchers and clinicians who plan to use the device for exercise and muscle performance measurement with patients.

The Kin-Com^R consists of several components. Subject testing and exercise is controlled by the operator using a personal computer and a software program supplied with the

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[2] Cybex Division of Lumex, Inc. 2100 Smithtown Ave., Ronkonkoma, NY 11779

device. Signals from the Kin-Com[R]'s force, angle, and speed transducers are processed at 100 Hz[3] by the system's analog-to-digital board and displayed on the computer CRT. Subjects can be placed in a variety positions for testing and exercise. The limb which is to be tested is physically attached to the dynamometer with a padded cuff which is attached to a housing containing strain gauges. The housing can be moved by the operator along a metal lever arm to accommodate different limb lengths. In the isokinetic mode the software allows the investigator to control the speed at which the lever arm will move. If the subject attempts to accelerate a limb beyond the pre-set speed the machine is designed to resist with a force equal in magnitude but opposite in direction, thereby resulting in a constant angular speed of the limb. This has been termed "accommodating resistance" by Enoka (1988).

The software also allows regulation of several other variables by using a set-up menu. The Kin-Com[R] differs from some other dynamometers in that the subject does not actually move the lever arm. The lever arm is moved by a hydraulic motor which is controlled by the computer. The software allows the user to set a threshold value of force that the subject must generate before the lever arm will move. This is called the *initial force*. The user is also allowed to regulate the acceleration of the lever arm at the

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[3] This information was obtained from the Kin-Com[R] operation manual and discussions with the manufacturer.

beginning of motion and deceleration of the lever arm at the end of motion by setting the *turn points* to high, medium, or low.

There are several commercially available electromechanical dynamometers that allow subjects to perform concentric contractions. The Kin-Com^R, like some other dynamometers, also allows subjects to perform eccentric contractions. In this case the machine provides a force that overcomes the force produced by the subject. As a result the limb segment moves in a direction that lengthens the muscle and an eccentric contraction takes place.

In order to perform these functions the Kin-Com^R monitors the force, angle, and speed signals. This is done through feedback loops which monitor the signal transducers. Force measurements are obtained by load cells in the lever arm. Angle measurements are obtained by a potentiometer and speed measurements by a tachometer.

The purpose of this study was to assess the performance characteristics of the Kin-Com^R dynamometer under controlled conditions. Measurements obtained from the Kin-Com^R, and simultaneous measurements obtained from our external recording system, were compared with known weights, angles, and speeds. These relationships were examined without subject interaction to furnish information not provided by the manufacturer. We consider this form of testing a prerequisite to further use of a device to obtain measurements.

METHODS

This section is divided into three parts. The first part concerns the methods used for testing the Kin-Com's[R] force measurements. The second and third parts describe the methods used to assess the Kin-Com's[R] angle and speed measurements.

In all three parts of the study the analog signals from the three Kin-Com[R] transducers were collected by an external recording system. These data were collected for comparison with the known values and the measurements obtained from the Kin-Com's[R] analog-to-digital processor. The external recording system consisted of an AMM1 analog-to-digital board in a Keithley DAS Measurement and Control System (Series 500).[4] Data acquisition was controlled by Dadisp I software[5] using an IBM XT personal computer.[6] Signal analysis was performed using Dadisp Worksheet.[7] The

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[4] Keithley Instruments, Inc., PO Box 391260, Cleveland, Ohio 44139

[5] Dadisp I, Version 1.0; DSP Development Corporation, 1 Kendall Square, Cambridge, MA 02139

[6] International Business Machines Corporation, Boca Raton, Florida 33429

[7] Dadisp Worksheet, Version 1.5; DSP Development Corporation, 1 Kendall Square, Cambridge, MA 02139

specific device tested was the Kin-Com^R dynamometer (model #500-11); testing procedures were controlled with Kin-Com^R software version 1.3.

Force Measurements

The Kin-Com^R measures forces applied in either of two directions. Load cells consisting of four strain gauges are mounted in a housing on the lever arm. The housing slides along the lever arm to accommodate different limb lengths. These strain gauges are mounted in pairs on the top and bottom of a metal shaft in the load cell and can, therefore, measure force generated by a limb in two directions. In this study each pair of strain gauges was tested separately so that force measurements in each direction could be evaluated. This was done by labelling one strain gauge pair as "1" and the other pair as "2" (Fig. 1) and applying the complete range of loads to each pair independently.

All force measurements were obtained by placing known weights on a weight pan which was suspended from the Kin-Com^R's lever arm. The testing of the Kin-Com^R's force measurement system was conducted on two consecutive days. For this part of the study the lever arm was maintained in a position perpendicular to the line of gravity. This position was determined with a gravity referenced protractor and maintained by placing a hydraulic jack under the lever arm.

Static force measurements can be obtained by using the gravity correction menu selection in the Kin-Com^R's software. This mode allows the tester to obtain force measurements by directly applying weights to the lever arm. Using this mode the following measurements were obtained on each testing day. First, a baseline voltage measurement was obtained. Next, a voltage calibration factor was determined for conversion of voltage to newtons. Last, the nature of the relationships between the force measurements obtained with the Kin-Com[R] measurement system, the external recording system, and the known weights were assessed.

Determination of Baseline Voltage for the Load Cell

The purpose of this part of the study was to assess the Kin-Com's[R] force measurement system. In order to accurately measure the applied loads we first needed to measure the load contribution of the weight pan alone. This measurement was then subtracted from subsequent load measurements. This procedure was conducted for both pairs of strain gauges on the two consecutive testing days. The housing containing the strain gauges also contains a removable bar for the subject attachment pad. This pad was removed and the bar alone was used for attachment of the weight pan. The weight pan was placed on this bar in a standardized position and locked with a clamp. The analog force signal in this condition was collected for one second at 50 Hz with the external recording system. Because of the static nature of this measurement we believed that a sampling frequency of 50 Hz was adequate. This signal was considered the baseline voltage in the system due to weight pan and was subtracted from force signals that were subsequently obtained with the known weights.

Determination of the Voltage Calibration Factor

A voltage calibration factor was calculated to be used to calculate the measured loads from our voltage signals. The calibration factor converted voltage to newtons and was determined for each pair of strain gauges on each day of testing. The calibration factor was calculated by loading the lever arm with the maximum amount of weight our weight pan could accommodate (48.51 kg [475.4 N]). The force signal generated by this load was sampled at 50 Hz for one second. The calibration factor was determined by use of the following equation:

$$\frac{475.4N}{mean\ \mu V^{475.4N} - mean\ \mu V^{baseline}} = N/\mu V \qquad (1)$$

See Table 1 for the calibration factors.

Relationship Between Known Weights and Measured Loads

This part of the study consisted of loading the weight pan with known weights ranging from 22.17 N to 453.23 N. Twenty different loads within this range were applied to the weight pan. The loads were increased by approximately 22 N from the lowest to the highest amount. The presentation of the 20 different loads was randomized for each test and the weight pan was unloaded after each load was applied. This loading procedure was performed for each pair of strain gauges on both testing days. The force signal for each load was collected by our external recording system at 50 Hz for one second. In addition, the force measured by the Kin-Com^R's measurement system was also recorded.

Angle Measurements

The Kin-Com^R measures the angular position of the lever arm with a potentiometer. The second part of the study was conducted to assess the relationship between angular positions of the lever arm as set with a gravity referenced protractor and measurements obtained with the Kin-Com^R's measurement system. Measurements were obtained on two consecutive days. A voltage calibration factor for conversion of voltage to degrees was first determined on each testing day. Next, the nature of the relationships between the angle measurements obtained with the Kin-Com^R measurement system, the external recording system and the set angles was assessed.

Determination of the Voltage Calibration Factor for the Potentiometer

A calibration factor in degrees/volt (°/V) was calculated in order to convert voltage signals to degrees. A voltage signal was obtained for one second at 50 Hz at the angles of 105° and 0° relative to a vertical position (as determined with a gravity referenced protractor). The calibration factor was determined by use of the following equation:

$$\frac{105^\circ}{mean\ \mu V^{105^\circ} - mean\ \mu V^{0^\circ}} = {}^\circ/\mu V \qquad (2)$$

See Table 1 for the calibration factors.

Relationship Between Set Angles and Measured Angles

A gravity referenced protractor was used to set the lever arm at the desired angles. The lever arm was initially placed in a horizontal position and this position was considered 0°. The voltage generated at this position by the potentiometer, therefore, represented the voltage for the potentiometer at 0°. The protractor was then used to set the angular position of the lever arm in 5° increments from 0° to 110°. At each angular position measurements were obtained from both the external recording system and the Kin-Com[R] measurement system. The voltage signal from the potentiometer was collected with our external recording system for one second at 50 Hz at each angular position. The Kin-Com[R] angular measurements were obtained from the test program screen. This is a calibration screen that can be accessed in the software. This screen displays a number representing the angle of the lever arm after processing the potentiometer signal through the Kin-Com[R]'s analog-to-digital board. This procedure was carried out on two consecutive days.

Speed Measurements

In this study we compared actual speeds of the lever arm with user-selected (set) speeds. We also examined several other aspects of the Kin-Com[R]'s performance relating to the control of lever arm speed. We felt that this was necessary because of the importance of lever arm control in this type of device. The actual speed of the lever arm was determined from the angular displacement signal using the data analysis software.

Relationships Between Set Speed and Actual Speed

Movement of the lever arm is controlled with the software selection menus on the Kin-Com[R]'s computer. Using the set-up menu *constant speed* in the *concentric/concentric* mode was selected. *Initial force*, the minimum force applied to the strain gauge necessary before movement is initiated, was set at 0 N. This setting caused the lever arm to move during testing without the need for an externally applied force. The lever arm was set to move through a 100° arc of motion from a position of -5° to 95°. When the lever arm was in the horizontal position it was considered to be at 90°, and when the lever arm was in the vertical down position it was considered to be at 0°. These positions were verified by use of a gravity referenced protractor. This 100° arc was re-set prior to each upward and downward movement of the lever arm. The start and stop angles were measured with the protractor and by the Kin-Com[R]. At each speed/acceleration/deceleration combination the movement in the upward direction was tested first followed by the downward movement.

The frequency of signal acquisition on our external recording system for this part of the study was 500 Hz. We felt this sampling frequency was necessary because the lever arm would be moving at speeds as high as 210°/sec. The rate of 500 Hz was the maximum sampling frequency our recording system would allow when sampling three channels (angle, speed, and force).

The speed of the Kin-Com[R] lever arm was tested without any externally applied force. The speeds tested were in 30°/sec increments through a range from 30°/sec to 210°/sec. Each speed was tested with all possible acceleration and deceleration combinations (high, medium, and low) and in both directions (upward and downward). The testing order of the speed/acceleration/deceleration combinations was randomized. Each of the combinations was tested on two consecutive days and the order of testing of the 126 permutations was randomized separately for each day.

Determination of Actual Speed

The speed that the lever arm moved was determined by the rate of displacement as calculated by use of the angle recording. The speed and angle recordings were evaluated using the data analysis software. The speed recording was examined to determine the beginning of motion, the beginning and end of the constant speed, and the point where the voltage returned to baseline.

DATA ANALYSIS

Data analysis was performed separately for each signal tested. For each of the following variables the strength of the linear relationship was analyzed using a coefficient of determination (r^2).

1. actual weights vs. externally recorded measurements
2. actual weights vs. measurements obtained from Kin-Com[R]
3. actual angles vs. externally recorded measurements
4. actual angles vs. measurements obtained from Kin-Com[R]
5. user selected speeds vs. externally recorded measurements

The coefficients of determination were calculated with a software program (QuattroPro[8], Ver. 1.0). In addition, Intraclass correlation coefficients (ICC, [1,1]) (Shrout & Fleiss, 1979) were calculated to assess the degree of agreement (reliability) between days for the externally

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[8] Borland International Inc., 1800 Green Hills Road, P.O. Box 660001, Scotts Valley, CA 95066-0001

recorded measurements and the Kin-Com[R] measurements. This form of the ICC was used because individual ratings were used to determine reliability and this form is a conservative measure of the reliability of paired observations.

RESULTS

The results from part one of the study are summarized in Tables 2 and 3. In all conditions the coefficient of determination (r^2) for the force measurements was above .99 (Table 2). The agreement (ICC) between days for all conditions was also above .99 (Table 3).

The results from part two of the study are summarized in Tables 4 and 5. In all conditions the coefficient of determination (r^2) for the angle measurements was above .99 (Table 4). The agreement (ICC) between days for all conditions was 1.00 (Table 5).

The results from part three of the study are summarized in Tables 6 and 7. In Table 6 the coefficient of determination (r^2) for the speed measurements was above .99 for all conditions. When various selected aspects of the speed measurements were considered the r^2 values were somewhat lower but never lower than .83 (Table 7).

During testing we noted that the lever arm did not always travel through the full user-set arc of motion. We observed that the greatest excursion at constant speed was achieved with slow speeds and high acceleration and deceleration settings. The loss of motion never exceeded four degrees in either the upward or downward directions with the largest amount of motion lost when the low deceleration setting was used.

DISCUSSION

Force Measurements

There was a nearly perfect linear relationship between known weights loaded on a weight pan suspended from the Kin-Com^R's lever arm and both the measurements obtained from the external recording system and the measurements obtained from the Kin-Com^R's software (see Table 2). Also, a high degree of agreement between days was shown to exist between the force measurements obtained with the external recording system and the measurements obtained by use of the Kin-Com^R (Table 3).

These findings are important for several reasons. We were able to sample the analog force signal from the strain gauges at 500 Hz with our external recording system. This means that we were able to obtain 400 more data points per second than the Kin-Com^R's measurement system (which samples at 100 Hz). Although our measurements were based on more data points and should, therefore, be potentially more accurate the coefficients of determination for the measurements obtained with the Kin-Com^R were similar. Therefore, not only does a linear relationship exist between the measurements obtained with our Kin-Com^R and known weights, but the strength of association measure (r^2) indicates that in our study approximately 99% of the variance in one set of measurements is accounted for by the other set of measurements. The lower sampling rate of the Kin-Com's[R] measurement system appears to be adequate for obtaining accurate measurements of applied loads under the type of conditions we tested.

This finding is important because static force measurements of the subject's limb are performed during the gravity correction procedure. It has been demonstrated that there is significant error associated with isokinetic torque measurements not corrected for the effect of gravity (Fillyaw, Bevins, & Fernandez, 1986; Winter, Well, & Orr, 1981). Whereas the findings in this study cannot be directly extrapolated to static force measurements of a subject's limb (and the associated error due to limb attachment and positioning) it does provide information as to the performance characteristics of the strain gauges during static loading. Also, more recent versions of the Kin-Com[R] software (ver. 3.01) allow testing of subject's isometric torque.

The intercepts of the lines describing the linear relationships between the measurements obtained with the Kin-Com[R] and the known forces are higher than for the other relationship (see Table 2). This discrepancy existed because we were unable to subtract the initial voltage due to the weight pan from the force values with the Kin-Com[R] software.

Our results were in agreement with those of Farrell and Richards (1986). These authors did not report the Kin-Com^R model or the software version used in their study. They tested the relationship between actual force measurements and measurements reported from the Kin-Com^R software by loading the lever arm with known weights in 22.3 N increments from 22.2 N to 310.8 N. They reported an ICC (RI [1,5]) of .99 after repeatedly loading and unloading the Kin-Com^R's lever arm. They do not reference the source of their ICC or why they used that particular form of the statistic.

The methods employed by Farrell and Richards (1986) to test this relationship were somewhat different than ours. The static loading part of their study consisted of positioning the lever arm at 10° increments from a horizontal (0°) to a vertical (90°) position. They applied the full range of their known weights to the lever arm at each angular position. They reported that they compared the measurements of their known weights to the measurements obtained from the Kin-Com^R only. Because we were unaware of the algorithm used by the Kin-Com^R software to analyze the force signals we independently processed the signal through our own analog-to-digital system to check the accuracy of the Kin-Com^R's force measurements.

Angle Measurements

The results presented in Table 4 demonstrate that there was a nearly perfect linear relationship between actual angular positions of the lever arm as determined with a gravity referenced protractor and both the measurements obtained with the external recording system and the measurements obtained from the Kin-Com^R's software. Also, a high degree of agreement was shown to exist between days for the angle measurements obtained with the external recording system and the Kin-Com^R (see Table 5).

Our findings indicate that when the signals generated by the Kin-Com^R's potentiometer are properly referenced they represent angles determined with a gravity referenced protractor. The study performed by Farrell and Richards (1986) also examined the relationship between angle measurements determined with an external recording device and angle measurements obtained with the Kin-Com^R. They compared angle measurements obtained with a spirit level and a protractor to measurements taken by the Kin-Com^R software. The authors reported that they positioned the lever arm at "various" angles and compared the Kin-Com^R's reported angles to the known angles. They did not provide a statistical analysis of this relationship but stated, "It was not possible to determine any difference in lever arm measurement made by either the Kin-Com^R or the external system". Therefore, while it not possible to precisely compare our results because of different methodologies, it would appear that our results generally agree with those of Farrell and Richards (1986).

Speed Measurements

The results presented in Table 6 demonstrate that constant speed measurements obtained with our external recording system have a nearly perfect linear relationship with the user-selected speeds tested in this study. These measurements also show a high degree of agreement when compared on two different days. When various components of the speed signal are examined these measures demonstrated a strong linear relationship and high degree of agreement between days (see Table 7).

The loss of lever arm motion was only noted during the use of medium and low acceleration and deceleration settings. We never observed a loss of motion when using the high settings. While the loss of motion never exceeded four degrees, and our study did not determine if this effect would be different if a subject were applying a force to the lever arm, we felt there was sufficient data to warrant the use of the high settings during further investigations. Clinicians and researchers using the Kin-Com[R] should be aware that the use of low and medium acceleration/deceleration settings may result in a decreased excursion of the lever arm. This effect may lead to inaccurate measurements and result in unreliable data.

Our study was designed to assess the accuracy of the signals from the Kin-Com's[R] transducers without subject involvement to provide information not available from the manufacturer. The results of this study cannot be extended to the use of the device when subjects are applying a force on the lever arm.

CONCLUSION

A strong linear relationship was shown to exist between the signals from the Kin-Com[R] transducers and known weights, angles, and user-selected speeds when tested under conditions not involving subject participation. There was also a strong linear relationship between values obtained from the Kin-Com[R]'s processing system and known weights and angles. The results of this study show that there may be a discrepancy between the user-selected excursion and the actual excursion of the lever arm when other than high acceleration and deceleration options are used. Our results indicate that the static measurements of force and angle that are necessary for use in the gravity correction procedure are accurate and reliable between days.

Table 1. Voltage Calibration Factors for Strain Gauges and Potentiometer

Strain Gauges	Calibration Factor (N/V)
Day 1 (position 1)	199.18
Day 1 (position 2)	193.90
Day 2 (position 1)	196.19
Day 2 (position 2)	196.80

Potentiometer	Calibration Factor (°/V)
Day 1	25.58
Day 2	25.57

Table 2. Linear Relationships Between Force Measurements

	Actual vs. External[a]			Actual vs. Kin-Com[Rb]		
Day	r^2	Slope	Intercept	r^2	Slope	Intercept
Measurements obtained on Day 1 (SG1[c])	.99	0.99	-0.02	.99	1.02	11.94
Measurements obtained on Day 2 (SG1)	.99	1.01	-2.32	.99	1.05	9.11
Measurements obtained on Day 1 (SG2[d])	.99	0.98	0.77	.99	1.04	6.61
Measurements obtained on Day 2 (SG2)	.99	1.00	-0.85	.99	1.04	5.37

[a] Applied force compared to measurements obtained with external recording system.

[b] Actual force compared to measurements obtained with Kin-Com[R] software.

[c] Strain gauge pair 1.

[d] Strain gauge pair 2.

Table 3. Reliability Estimates of Force Measurements Between Days

Type of Measurement	ICC[a]
Measured (SG1[b])	.99
Measured (SG2[c])	.99
Kin-Com[R] (SG1[d])	.99
Kin-Com[R] (SG2[e])	.99

[a] Intraclass correlation coefficient [1,1].

[b] Externally recorded force measurements from strain gauge pair 1, day 1 vs. day 2.

[c] Externally recorded force measurements from strain gauge pair 2, day 1 vs. day 2.

[d] Kin-Com[R] force measurements from strain gauge pair 1, day 1 vs. day 2.

[e] Kin-Com[R] force measurements from strain gauge pair 2, day 1 vs. day 2.

Table 4. Linear Relationships Between Angle Measurements

	Actual vs. External[a]			Actual vs. Kin-Com[Rb]		
Day	r^2	Slope	Intercept	r^2	Slope	Intercept
Measurements obtained on Day 1	.99	1.00	0.09	.99	1.00	-0.05
Measurements obtained on Day 2	.99	1.00	-0.02	.99	0.99	0.04

[a] Actual angle compared to measurements obtained with the external recording system.

[b] Actual angle compared to measurements obtained with Kin-Com[R] software.

Table 5. Reliability Estimates of Angle Measurements Between Days

Type of Measurement	ICC[a]
External[b]	1.00
Kin-Com[R][c]	1.00

[a] Intraclass correlation coefficient [1,1].

[b] Externally recorded angle measurements, day 1 vs. day 2.

[c] Kin-Com[R] angle measurements, day 1 vs. day 2.

Table 6. Linear Relationships and Reliability Estimates of Speed Measurements

Conditions	r^2	Slope	Intercept	ICC[a]
Set vs. Actual[b]				
Day 1	.99	1.01	-1.43	.99
Day 2	.99	1.01	-1.49	.99
Day 1 (up)[c]	.99	1.01	-1.23	.99
Day 2 (up)	.99	1.01	-1.29	.99
Day 1 (down)[d]	.99	1.01	-1.64	.99
Day 2 (down)	.99	1.01	-1.61	.99
Actual Speed[e]				
Day 1 vs. Day 2	.99	1.00	-0.01	1.00
Day 1 vs. Day 2 (up)	.99	1.00	-0.06	1.00
Day 1 vs. Day 2 (down)	.99	0.99	0.03	1.00

[a] Intraclass correlation coefficient [1,1].

[b] User-selected speed compared to actual speed of lever arm calculated from rate of displacement of lever arm.

[c] Upward movement of lever arm.

[d] Downward movement of lever arm.

[e] Actual constant speed calculated from rate of displacement of lever arm.

Table 7. Linear Relationships and Reliability Estimates for Specific Speed Measurements

	Day 1 vs. Day 2			
Conditions	r^2	Slope	Intercept	ICC[a]
Excursion at constant speed[b]	.96	0.98	2.34	.91
Time at constant speed[c]	.99	1.00	0.01	.99
Actual Excursion[d]	.85	0.94	6.37	.99
Mean Voltage[e]	.99	0.99	0.00	.99
Acceleration[f]	.99	0.99	0.00	.99
Deceleration[g]	.83	0.82	6.92	.88

[a] Intraclass correlation coefficient [1,1].

[b] Excursion of lever arm while moving at constant speed.

[c] Amount of time the lever arm is moving at constant speed.

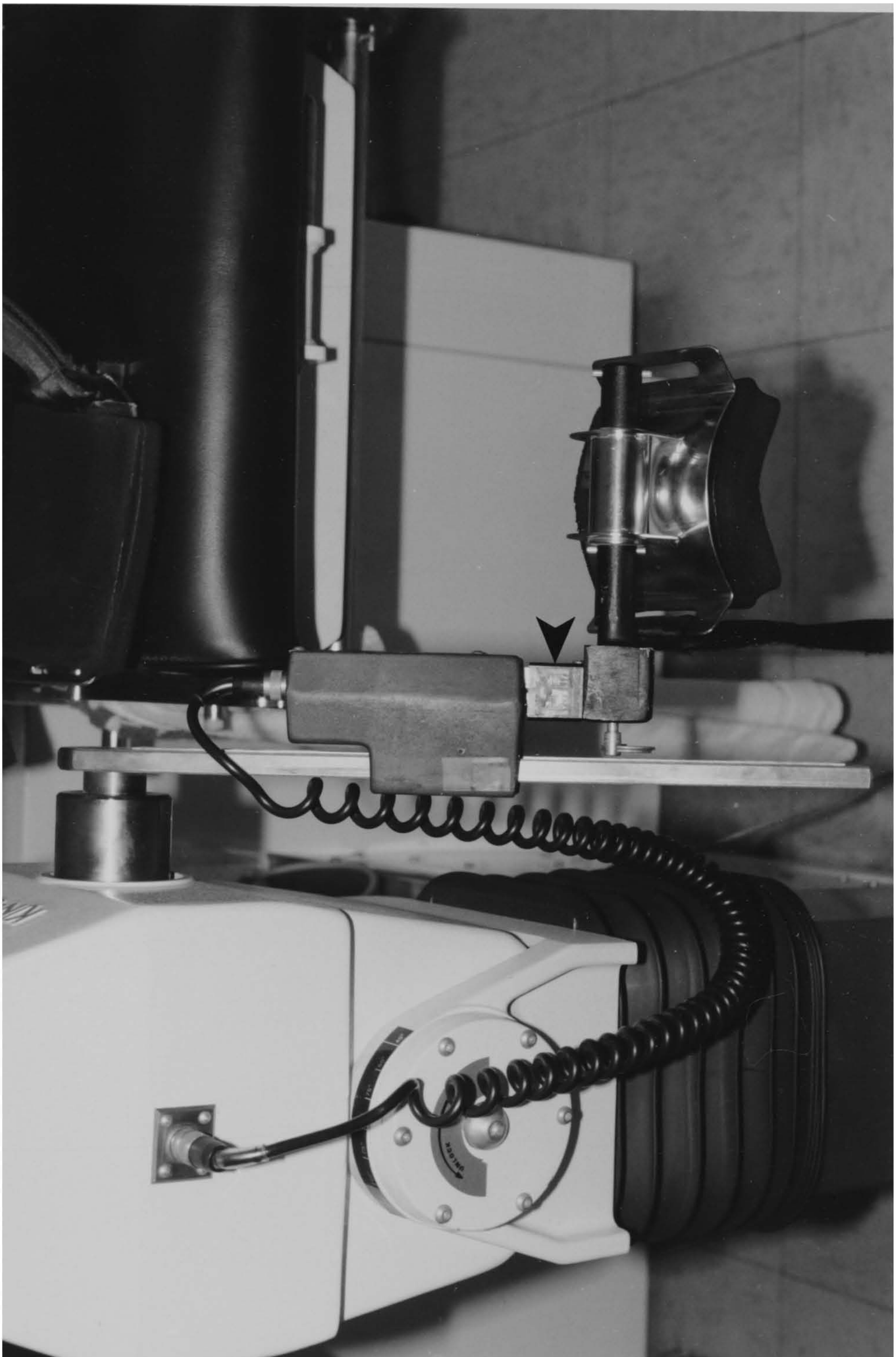
[d] Actual full excursion of lever arm.

[e] Mean voltage recorded during constant speed portion of lever arm movement.

[f] Speed from start to constant speed portion of lever arm movement.

[g] Speed from constant speed portion of lever arm movement to stop.

Figure 1. This figure shows the location of the strain gauges mounted in the housing on the lever arm.



PART 2

The Effects of Concentric and Eccentric Contractions Performed at Equal Power Levels on Skeletal Muscle Fiber Hypertrophy

This chapter is to be submitted for publication in *Muscle & Nerve*.

The Effects of Concentric and Eccentric Contractions Performed at Equal Power Levels on Skeletal Muscle Fiber Hypertrophy

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ABSTRACT

The purpose of this study was to investigate the effect of training with concentric and eccentric muscle contractions on skeletal muscle hypertrophy and isometric torque production. Twenty normal subjects were randomly assigned to two groups. Both groups exercised three times per week for four weeks on the Kin-Com dynamometer. One group (8 females, 2 males, mean age = 22.9 years, SD = 2.96) performed concentric contractions of their right quadriceps femoris muscle at an intensity of 90% of their maximal concentric power through a range of 75° of knee extension (15° to 90°). The other group (6 females, 4 males, mean age = 24.1 years, SD = 4.38) performed eccentric contractions of the same muscle at the same relative power level. Both groups exercised at a constant speed of 60°/sec. Needle muscle biopsies were obtained from the vastus lateralis muscle before and after the exercise program. Muscle fiber type differentiation was performed using a myosin adenosine triphosphatase (ATPase) stain at an alkaline preincubation. The percent change in fiber area was determined for each fiber type in each subject and a one-way ANOVA (between groups) was used to analyze the data. Our results showed a significant difference between the groups. The type II fibers of the concentric group exhibited a greater percent increase in area as compared to the eccentric group. Maximal isometric knee extension torque was determined at 60° of knee flexion for each subject before

and after the exercise program using the Kin-Com[R]. The percent change in isometric torque was determined for each subject and a one-way ANOVA (between groups) was performed on the data. The concentric group increased maximal isometric torque production more than the eccentric group. Our results indicate that when exercising at the same relative power level a subject performing concentric contractions will 1) show greater muscle hypertrophy and, 2) improve in isometric torque production more than a subject training with eccentric contractions. Therefore, the results of our study suggest that a concentric exercise program may be preferable to an eccentric program if the goal is fiber hypertrophy and improved force production.

INTRODUCTION

Rehabilitation professionals often attempt to alleviate skeletal muscle weakness by prescribing exercise according to the overload principle. This principle implies that exercise must exceed a certain threshold of force in order for a muscle to increase in size or to improve in performance (Enoka, 1988). The force level necessary for optimal muscle hypertrophy is not known (Atha, 1981). According to Komi and Buskirk (1972), the primary stimulus for muscle hypertrophy is the production of tension above the levels normally produced by those muscles. Activities of daily living, however, require both concentric and eccentric contractions at varying speeds and magnitudes (Dean, 1988).

The adaptive response of human skeletal muscle to concentric and eccentric exercise has been studied by a number of investigators (Duncan, Chandler, Cavanaugh, Johnson & Buehler, 1989; Ellenbecker, Davies & Rowinski, 1988; Johnson et al., 1976; Komi & Buskirk, 1972; Mannheimer, 1969; Pavone & Moffat, 1985; Petersen, 1960; Singh & Karpovich, 1967). Currently it is not known whether exercising with one type of contraction is more effective than the other for producing muscular hypertrophy (Atha, 1981). In recent years there has been considerable interest in the use of eccentric contractions for improving muscle force production. Skeletal muscle is able to generate greater levels of tension during eccentric contractions than during either concentric or isometric contractions (Doss & Karpovich, 1965; Olson, Smidt & Johnston, 1972; Singh & Karpovich, 1966). Some investigators, therefore, propose that eccentric exercise programs provide a better stimulus for hypertrophy and improved muscle force production than do programs including other types of contractions (Atha, 1981; Johnson, Adamczyk, & Tennoe, 1976; Walmsley, Pearson & Stymiest, 1986).

Mechanisms of Skeletal Muscle Hypertrophy

The increase in size of skeletal muscle as a result of heavy resistance training is generally believed to be due to enlargement of individual muscle fibers (Tesch & Larsson, 1982). The enlargement of the muscle fibers is a result of enhanced protein synthesis and increased size and number of myofibrils (Goldberg et al., 1975; Goldspink, 1964). The mechanisms responsible for triggering the enhanced protein synthesis are not known (MacDougall, 1986). One possible stimulus for the increased uptake of amino acids and subsequent protein synthesis is the amount of tension that a muscle develops while contracting (Booth, 1982).

An experimental model in which the gastrocnemius muscle of rats was tenotomized provided evidence to support this hypothesis (Goldberg, 1975). This procedure, which led to a phenomenon commonly called "compensatory overload," resulted in an increased workload on the synergistic plantaris and soleus muscles. Hypophysectomized rats with a tenotomized gastrocnemius show after five days of normal activity weight increases in the soleus of 30% to 50% and in the plantaris of 20% (Goldberg, 1967). The weight of the soleus and plantaris muscles increased even further if the rats were forced to exercise on a treadmill. The mean fiber diameters of the muscles of the tenotomized limbs were significantly greater than those of controls. A relative increase in muscular tension appears to be a potent stimulus for muscle hypertrophy in animal models. This effect appears to be independent of hormonal influences (Goldberg, 1975).

Another possible stimulus for muscle fiber hypertrophy is termed by MacDougall (1986) as the "break down and build up theory." He suggests that fiber hypertrophy in response to strength training may be the result of a repair process. He argues that muscular contractions against heavy loads may damage contractile and connective tissue components. These components are then repaired during the days between exercise sessions. Fiber hypertrophy may, therefore, be the result of an adaptive increase in protein synthesis in response to a damaging tensile demand. Morphological evidence for this theory has been provided in humans by Friden, Sjostrom, and Ekblom (1983). They found disruptions in the Z bands and marked disturbances in myofibrillar organization in type II fibers of subjects that performed intense bouts of eccentric exercise.

Newham, McPhail, Mills, and Edwards (1983) compared the ultrastructural effects of concentric and eccentric exercise. They found no structural abnormalities in muscle biopsies from subjects exercising concentrically or from non-exercising controls. Structural changes in the subjects exercising eccentrically were consistent with those of Friden et al. (1983). Newham et al. (1983) concluded that the damage found in the subjects exercising eccentrically was due to the greater amounts of tension generated per fiber in that group.

Muscular Adaptation to Training with Concentric and Eccentric Contractions

Proponents of eccentric exercise argue that if the critical stimulus for increased protein synthesis is tension, then training with eccentric contractions will provide a more intense stimulus resulting in greater strength gains (Atha, 1981). Evidence to support this theory is provided by two studies in which concentric and eccentric exercises were compared (Komi & Buskirk, 1972; Mannheimer, 1969). In both of these studies subjects exercising eccentrically showed greater improvements in force production than subjects exercising concentrically. Other investigators have, however, found that neither contraction type was superior to the other for producing improvements in force production. (Johnson, Adamczyk, & Tennoe, 1976; Pavone & Moffat, 1985). After reviewing the literature, Atha (1981) concluded that "eccentric training is effective in increasing strength, but is no more effective than either isometric or concentric training."

Studies comparing concentric and eccentric exercise have usually examined the effects of maximal contractions (Duncan, Chandler, Cavanaugh, Johnson & Buehler, 1989; Ellenbecker, Davies & Rowinski, 1988; Johnson et al., 1976; Komi & Buskirk, 1972; Mannheimer, 1969; Pavone & Moffat, 1985; Petersen, 1960; Singh & Karpovich, 1967). At a given velocity of limb movement, however, a subject can generate more torque during a maximal eccentric contraction than during a maximal concentric contraction (Komi, 1986; Komi & Buskirk, 1972). The subjects performing eccentric contractions would, therefore, be exercising with a higher level of torque than subjects performing concentric contractions. The results from these experiments would not provide clear evidence of adaptations as a consequence of contraction type alone. Any differences that were found may have been attributable to the non-equivalence of the exercises.

The dependent measure most commonly used to assess the effectiveness of concentric and eccentric exercise is improvement in maximal force production (Johnson et al., 1976; Komi & Buskirk, 1972; Mannheimer, 1969; Pavone & Moffat, 1985). Improvement in maximal force production is often calculated from pre and post exercise measurements using the contraction type in which the subject trained. These measurements may have indicated an improvement in their subject's ability to perform the specific type of contraction. This may represent a skill enhancement and not a biological change (Sale, 1986). Improvement in the performance of this skilled movement may not be generalizable to other functional activities. Exercise programs designed to improve the force production capability of skeletal muscle usually involve heavy resistance training (high loads with few repetitions). Studies have shown that this method of training results in an increase in the cross-sectional area of type I and type II fibers, with a far greater amount of hypertrophy in the type II fibers (Edgerton, 1978; Thorstensson, 1976). A more meaningful dependent measure of biological change, free from the influences of skill enhancement, therefore, would be measurements of the change in fiber area.

Studies have been conducted which have examined the differences between concentric and eccentric exercise using comparable workloads. Eccentric contractions have been shown to be more efficient than concentric contractions relative to oxygen consumption per unit of tension (Abbott, Bigland & Ritchie, 1952; Asmussen, 1952; Bigland-Ritchie & Woods, 1976), and the amount of ATP required per unit of tension (Infante, Klaupiks & Davies, 1964; Knuttgen & Klausen, 1971). Eccentric contractions have also been shown to require fewer active motor units, with a lower frequency of activation, than concentric contractions at the same force and speed of contraction (Abbott et al., 1952; Bigland & Lippold, 1954; Bigland-Ritchie & Woods, 1974; Moritani, Muramatsu & Muro, 1988).

No studies were found that compared the effect of concentric and eccentric exercise on muscle fiber hypertrophy. In order to answer the question of which type of contraction is more effective in producing muscle fiber hypertrophy, the subjects in each exercise group would have to exercise at equivalent loads. The speed of limb movement and the torque produced during the contraction, therefore, must be controlled. Power is a measurement that takes both of these variables into account. Subjects exercising at equivalent power levels may show a smaller percentage increase in muscle fiber area in eccentrically trained muscle as compared to concentrically trained muscle. The reason for this is that eccentric contractions are more efficient and subjects trained eccentrically should be able to maintain a given power level with less of a stimulus for hypertrophy than the concentrically trained group.

The purpose of this study was to determine if there was a difference in the percent change of fiber area in the vastus lateralis muscle as a result of concentric and eccentric exercise at equal power levels. A second purpose was to determine if there was a difference in the percent change of maximal isometric torque in the quadriceps femoris muscle as result of concentric and eccentric exercise at equal power levels.

METHODS

Overview

Subjects were randomly assigned to one of two groups. One group of subjects performed eccentric contractions and the other group concentric contractions of their right quadriceps femoris muscles. All subjects exercised at the same relative power level throughout the study (i.e., 90% of their pre-exercise maximal concentric power). Needle biopsies of the right vastus lateralis muscle were performed before and after the exercise program. The exercise effect was evaluated by examining the percentage of change in cross-sectional area of type I and II muscle fibers, and the percentage of change in isometric torque production.

Subjects

The subjects in this study were 14 female and 6 male volunteers who:

1. had no physical or painful limitations in active or passive range of motion in their right hip or knee joints,
2. had no history of medical conditions that would hinder wound healing (e.g., diabetes),

3. had no cardiovascular, orthopedic, or neurological conditions that would contraindicate an exercise program consisting of approximately 20 minutes of exercise three times per week for four weeks,
4. agreed to continue their base levels of exercise throughout the duration of the study (physically active subjects (e.g., joggers, weight lifters, cyclists) must agree not to increase or decrease their normal activity levels), and
5. had read and signed a consent form before participating in the study.

The concentric subject group consisted of eight females and two males with an age range from 20 to 30 years (mean = 22.9, SD = 2.96). The eccentric subject group included six females and four males with an age range from 20 to 36 years (mean = 24.1, SD = 4.38).

Exercise Procedure

A Kin-Com^{R}[1] dynamometer (model #500-11, software version 3.01) was used to measure and control the power produced by the subjects in this study. The Kin-Com^{R} is a computer controlled electromechanical dynamometer that can be used to provide resistance to the movement of a subject's limb during testing and exercise. Calibration of the strain gauges (force signal), and potentiometer (angle signal) was

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[1] Chattecx Corp., 101 Memorial Drive, PO Box 4287, Chattanooga, TN 37405

evaluated before and after the exercise portion of this study. The strain gauges and the potentiometer of the Kin-Com[R] did not lose calibration.

Each subject exercised throughout the study at the same relative power level. The power level used was 90% of each subject's pre-exercise maximal concentric power level. Because control of power was a critical part of our methodology, the power generated during each muscle contraction was calculated. Power levels were controlled throughout the exercise portion of our study with target "markers" determined by use of the following procedure.

Each subject participated in a pre-exercise session. The purpose of the pre-exercise session was to determine each subject's maximal concentric quadriceps femoris muscle power during an isokinetic movement at 60°/sec. During this session the subject sat on the Kin-Com[R] bench with his back supported by the backrest and his right knee next to the lever arm. This position resulted in approximately 90° of hip flexion as determined by visual inspection. The location of the backrest was recorded for use in subsequent exercise sessions. The subject's shoe was removed and his right femoral epicondyle (indicative of the anatomical axis of rotation) was aligned with the axis of rotation of the lever arm. The pad of the Kin-Com[R]'s lever arm was attached to the subject's right leg one centimeter proximal to the medial malleolus. The distance from the lever arm's axis of rotation to the center of the pad was recorded and entered into the Kin-Com[R]'s computer as the limb length. This measurement was subsequently used to determine torque values.

The backrest was then removed and the subject was placed in a supine position on the bench for determination of the gravity correction value. This position was used because preliminary testing indicated that when subjects were sitting the measurement of leg weight was artificially high due to hamstring tightness. These studies also showed that leg weight measurements were more accurate when obtained with the lever arm in a horizontal position. The "*gravity correction*" routine in the Kin-Com[R]'s software was used to measure the weight of the leg in the horizontal position.

The subject was then repositioned in sitting and straps were placed across his pelvis and distal thigh. A goniometer was used to place the subject's knee in 90° of flexion. This value was entered into the Kin-Com[R]'s computer under the "*anatomical joint reference*" option. This procedure was conducted so that the angle of the lever arm corresponded with the angle of the subject's knee.

The subject was allowed to become accustomed to moving his limb while strapped to the Kin-Com[R] before power measurements were obtained. Subjects performed ten practice concentric quadriceps femoris muscle contractions through an arc of 75° (starting at 90° of knee flexion and ending at 15° of knee flexion). All practice contractions were performed at a speed of 60°/sec. After a ten minute rest the subject was instructed to perform ten maximal concentric quadriceps femoris muscle contractions. There was a 45 second rest between each contraction and force, angle, and speed measurements were recorded. Preliminary studies in our laboratory demonstrated that subjects would produce their maximal concentric contraction within the first ten contractions.

The Kin-Com^R's evaluation program was used obtain these measurements and to control the power levels during the exercise portion of the study. The set-up menu in the Kin-Com^R evaluation mode allows the user to select control parameters for exercise and testing. The type of movement ("*control constant*") was set for speed. This allowed us to obtain the torque measurements during constant speed limb movements (except for short periods of acceleration and deceleration). The type of contraction ("*motion*") was set to concentric/eccentric. The acceleration ("*turn point, acc.*") and deceleration ("*turn point, dec.*") of the Kin-Com^R's lever arm were set on high for two reasons. We wanted to maximize the amount of time the subject's limb moved at a constant speed, and, a pilot study indicated that use of the medium and low settings could result in the loss of lever arm motion[2].

The initial force setting ("*init. force*") allows the user to set a force required before the lever arm will move. We determined through preliminary testing that setting this

[2] See Part 1 of this dissertation.

option to 150% of the subject's leg weight allowed for an initial buildup of muscular tension and a smoother transition into movement. Therefore, the lever arm initial force "*forth*" was set to 150% of the subject's leg weight. The initial force "*back*" was set to zero which resulted in passive return of the lever arm to the start position. The lever arm was set to move in an arc from 90° to 15° of knee flexion. The speed of lever arm motion was set at 60°/sec.

During the pre-exercise session the analog signal from the Kin-Com^R's force, angle, and speed transducers was collected with an external recording system. This system consisted of an AMM1 analog-to-digital board in a Keithley DAS Measurement and Control System (Series 500)[3]. Data acquisition was controlled by Dadisp I software[4] using an IBM XT personal computer[5]. The measurements of peak torque, average torque, and average speed from the ten maximal concentric quadriceps femoris contractions were calculated using Dadisp Worksheet[6]. The power produced during each contraction was calculated by multiplying the average torque by the average speed for each contraction. The contraction producing the greatest amount of power was then identified.

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[3] Keithley Instruments, Inc., PO Box 391260, Cleveland, Ohio 44139

[4] Dadisp I, Version 1.0; DSP Development Corporation, 1 Kendall Square, Cambridge, MA 02139

[5] International Business Machines Corporation, Boca Raton, Florida 33429

[6] Dadisp Worksheet, Version 1.5; DSP Development Corporation, 1 Kendall Square, Cambridge, MA 02139

The training target power level for the exercise portion of the study was 90% of the power produced during this contraction.

Measurements of each subject's maximal isometric right quadriceps femoris torque was also obtained during the pre-exercise session. This measurement was repeated at the end of the exercise portion of the study and the percent change in each subject's maximal isometric torque was calculated. Isometric torque measurements were obtained using the Kin-Com^R's training program. This program allows the user to set "stop angles" at which the lever arm will pause for a specified amount of time. During this pause the subject can perform an isometric contraction against the immobilized lever arm.

In this study the lever arm was set to stop at 60° of knee flexion for three seconds. Each subject was instructed to contract their quadriceps femoris muscle maximally against the immobile lever arm. Two isometric torque measurements were obtained. This procedure was repeated during a session 24 hours after the end of the exercise portion of the study. The average isometric torque produced during the middle one second of the contraction with the highest torque production (for both the pre and post exercise sessions) was determined. These values were used to determine the percent change in maximal isometric torque.

The 20 subjects were randomly assigned to two groups consisting of ten subjects. One group performed concentric contractions, the other group performed eccentric contractions. The subjects were set up on the Kin-Com[R] as described for the pre-exercise session. The software settings for the concentric group were identical to those used in their pre-exercise session. The settings for the eccentric group differed only in that the initial force "*forth*" setting was zero, and the "*back*" setting was 150% of their leg weight. The exercise portion of the study consisted of three sessions per week for four weeks. During each exercise session the subjects performed five sets of ten quadriceps femoris muscle contractions. There was a two minute rest period between sets of muscle contractions. The ten contractions within a set were performed at whatever rate the subject felt comfortable, but with not more than 30 seconds between contractions.

Subjects in both groups attempted to match the power produced during each contraction with the target power level determined in the pre-exercise session. This was done by setting target "markers" on the Kin-Com[R] computer's CRT screen which represented 85% and 95% of the peak torque produced during the subject's concentric contraction producing the greatest power during session one. The subjects were instructed to watch the Kin-Com[R]'s CRT screen and push against the lever arm in such a way that they maintained their force tracing for as long as possible within the marker boundaries.

Preliminary studies performed in our laboratory demonstrated that subjects attempting to maintain their torque output within these training markers were able to produce power levels within ±10% of the target power. The power produced during each contraction was calculated for each subject for all twelve exercise sessions. An average percent target power was calculated for all the contractions performed in the exercise portion of the study. If the mean percentage of the target power was not within ±10% of the target power the subject was eliminated from the study and another subject was recruited.

Biopsy Procedure

Pre-exercise needle biopsies of the right vastus lateralis muscle were obtained during a period approximately 24 hours after the pre-exercise session and 48 hours before the start of the exercise program. Post-exercise biopsies were obtained within 72 hours after cessation of the exercise program. The biopsies were performed using the technique as described by Bergstrom (1962) with the suction modification of Evans (1982). The biopsy site was located approximately at the midpoint of the lateral aspect of the right thigh. A UCH Biopsy needle[7] with suction provided by a 50 cc. syringe was used to remove the muscle sample.

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[7] UCH Biopsy Needles, Surgical Division of Needles Industries, Ltd., PO Box 3, Redditch, Worcestershire, England.

The muscle sample was immediately oriented with a dissecting microscope so that cross-sections of the sample represented cross-sections of the muscle fibers. The samples were then mounted on cork with OCT embedding compound[8] and frozen in isopentane chilled in a liquid nitrogen bath. The frozen samples were placed in cryotubes and stored at -23°C for later analysis. Post-exercise biopsies were performed in an identical manner; however, the sample was obtained from a site approximately two centimeters distal to the previous site to avoid any scarring in the muscle tissue.

Analysis of Muscle Samples

A cryostat[9] was used to section the biopsy specimen (10-14 μm in thickness) in the transverse plane. The unfixed frozen cryostat sections were thaw-mounted on glass slides for histochemical analysis. Muscle fiber type differentiation was performed using a myosin adenosine triphosphatase (ATPase) stain at an alkaline preincubation (Dubowitz, 1985). All sections were pre-incubated in staining dishes at a pH of 10.5. The pre and post-exercise muscle sections from each subject were stained in the same staining dish as a control for differences in staining intensity.

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[8] Miles Laboratories Inc., Ames Div., Elkart, IN 46515.

[9] IEC Minot Microtome, International Equipment Co, 300 Second Ave, Needham Heights, MA 02194.

Light micrographs of each stained section were obtained with a Nikon Labophot automatic exposure photomicrographic system.[10] Each print was enlarged to 8 inches by 10 inches and covered with a clear plastic overlay. The muscle fibers in each micrograph were classified as type I or type II by examining the intensity of staining of each fiber. At the alkaline preincubation used in this study the type II fibers stained darkly and the type I fibers stained lightly (Fig. 1) (Brooke & Kaiser, 1970). Each fiber of a given type was consecutively numbered on the plastic overlay of each micrograph. A computer program[11] was used to generate a series of 50 random numbers for each fiber type. The lower bound of these numbers was one and the upper bound was the number of each type of fiber that was identified on the micrograph. Only those fibers specified in the random sampling procedure were measured.

Fiber areas were measured using a Bioquant micrograph digitizing system.[12] This system uses a light microscope and video camera to project the image of the micrograph on a video monitor. A graphics plate and mouse were then used to trace the perimeter of the muscle fiber. A personal computer and a software program were used to calculate areas in the

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[10] Nippon Kugaku K.K., Fuji Bldg. 2-3,3 chome, Marunouchi, Chiyoda-Ku, Tokyo 100, Japan

[11] Quattro, Borland International, 4585 Scotts Valley Dr., Scotts Valley, CA 95066

[12] Bioquant System IV, R & M Biometrics, Inc., 5611 Ohio Ave., Nashville, TN 37209

desired units. A 10x objective was used to project the image on the video screen.

The reliability of these measurements were tested on a randomly chosen pair of micrographs from one subject before using the system with the remainder of the subjects. The same investigator that performed the measurements of fiber areas for the entire study participated in the reliability study. Fifty randomly selected fibers of each type were measured from one subject's pre and post exercise biopsy samples (200 measurements). Area measures of the same fibers were repeated on the following day. An intraclass correlation coefficient (ICC) [1,1] was performed to assess the agreement between the measurements between days (Shrout & Fleiss, 1979). The ICC for this comparison was .99. This indicated a high degree of intra-rater reliability for these measurements when obtained on two consecutive days.

Data Analysis

The mean fiber area for each fiber type was calculated for pre and post-exercise biopsies for each subject. The percent change in fiber area between pre and post-exercise biopsies was then determined separately for each subject's type I fibers, type II fibers and for the type I and II fibers combined. A One-Way Between Subjects Analysis of Variance (ANOVA) was used to analyze the percent change in mean muscle fiber area between the concentric and eccentric exercise groups (Linton & Gallo, 1975). Three separate comparisons were made between the groups relative to percent change in fiber area. The first comparison was made to determine if there was a difference between the two exercise groups in percent change of mean type I muscle fiber area. The second comparison was performed to determine if there was a difference between the groups in percent change of mean type II fiber area. A third comparison was made to determine if there was a difference between the two exercise groups in the percent change of the combined type I and II mean fiber areas.

A One-Way Between Subjects ANOVA was also used to analyze changes in the subjects' isometric torque production. A comparison was made to determine if there was a difference between the two exercise groups in percent change of maximal isometric torque between pre and post exercise measurements.

RESULTS

Table 1 summarizes the percent changes in mean muscle fiber area between the exercise groups. Table 2 summarizes the percent changes in mean isometric torque between the exercise groups. A One-Way Between Subjects ANOVA for percent change of the combined type I and II mean fiber areas is summarized in Table 3. A difference was found between the groups with the concentric exercise group demonstrating a greater percent change in fiber area than the eccentric exercise group.

Table 4 is a summary of A One-Way Between Subjects ANOVA for percent change of type I mean fiber area. There was no difference between the groups.

A One-Way Between Subjects ANOVA for percent change of the type II mean fiber area is summarized in Table 5. A difference was found between the two exercise groups. The concentric exercise group showed a significantly greater percent change in fiber area compared to the eccentric exercise group.

A One-Way Between Subjects ANOVA for average percent change of maximal isometric torque is summarized in Table 6. A significant difference was found between the groups with the concentric exercise group exhibiting a greater percent change in maximal isometric torque than the eccentric group.

DISCUSSION

The results of our study indicate that there is a contraction type dependent difference in the change in muscle fiber area in normal subjects following an exercise program at the same relative power level. Our results also demonstrate that this difference is fiber type specific. The change in area of the type II fibers of the group that trained concentrically was significantly greater than the group that trained eccentrically. This was accompanied by a significantly greater increase in isometric torque production. The change in area of the type I fibers was not significantly different between the two groups.

Our finding that the type II fibers show a significantly greater amount of hypertrophy in the concentrically trained subjects agrees with studies that have described the physiological differences between contraction types. Abbott et al. (1952, 1953) demonstrated that a subject that was performing concentric contractions consumed more oxygen than a subject performing an equal amount of work with eccentric contractions. He hypothesized that fewer fibers were active per unit of force during eccentric contractions. Bigland-Ritchie and Woods (1974) confirmed this finding as well as provided electromyographic evidence that fewer muscle fibers were necessary to provide a given amount of force during eccentric contractions. Infante et al. (1964) showed that in the frog sartorius muscle eccentric contractions required 1/13th of the amount of ATP required during concentric contractions.

These findings indicate that eccentric contractions are more efficient than concentric contractions. It would follow that an exercise program consisting of eccentric contractions at a given power level would require less effort for subjects to perform than a similar concentric program. These subjects would not show as much fiber hypertrophy because the relative stimulus for hypertrophy would be less. Our findings support this hypothesis. At a given power level our concentric group showed a significantly greater amount of hypertrophy in their type II fibers. This evidence of cellular change was supported by a significantly greater improvement in isometric torque production by the concentric group.

The power levels in our exercise protocol were carefully monitored. The relative amount of total tension produced by each subject's quadriceps femoris muscle should have been the same in both exercise groups. According to Bigland and Lippold (1954) the number of motor units and the frequency of activation of those motor units is less for eccentric contractions than for concentric contractions at equivalent power levels. It is possible, therefore, that fewer motor units were recruited in the quadriceps femoris muscles in our eccentric exercise group. This may have resulted in a greater amount of tension per muscle unit in those recruited motor units. It has been suggested that the critical stimulus for muscle fiber hypertrophy may be an increase in the amount of tension produced by a contracting muscle fiber (Booth, 1982), or an increased relative use of a muscle (Goldberg et al., 1975). Therefore, a relatively greater amount of hypertrophy in the muscles trained eccentrically might have been expected. We found, however, a greater amount of hypertrophy in the muscles of the concentric group. Our results indicate that there was a greater change in the relative use of the muscles in the concentric group compared to the eccentric group. This may have been due to the greater efficiency of eccentric contractions at a given power level.

Comparing the results of our study to other studies that have investigated the difference between concentric and eccentric training regimens is difficult for several reasons. First, our primary dependent measure in this study was the change in fiber area associated with different types of training. We were unable to find any other similar studies in which this dependent measure was used. Second, we were interested in evaluating the difference between the two training programs (concentric and eccentric) using equivalent power levels. No other studies controlled their variables in this way. Most investigators have studied the difference between concentric and eccentric exercise programs using maximal contractions of each type. Because they were using maximal contractions their subject groups were exercising at different power levels. Also, we were interested in examining contraction type dependent differences in the quadriceps femoris muscle. Most other similar studies have studied contractions of muscles in the upper extremity.

Komi and Buskirk (1972) used a specially constructed dynamometer to investigate the improvement in right forearm flexor muscle performance as a result of isokinetic concentric and eccentric training. They had three groups of subjects: one group that performed maximal eccentric contractions; a second group that performed concentric contractions; and a third group that served as controls (no exercise). Their subjects participated in an exercise program consisting of six maximal concentric or eccentric contractions per day, four times per week, for seven weeks. The subjects were tested to determine their maximal isometric, concentric, and eccentric tension before, during, and after the seven week conditioning program.

The results of their study showed that the eccentric group improved significantly over the control group in isometric, concentric and eccentric maximal force. The concentric group improved significantly over the control group in concentric and eccentric maximal force, but not in isometric maximal force. They also state that on a percentage basis, the eccentric group increased maximal force more than the concentric group in all three measured forces, but this was only statistically significant for eccentric maximal force. The authors reported that soreness was felt by all the subjects in the eccentric group during the early phase of conditioning. They also stated that this group showed a sharp drop in force production during the first week of conditioning that corresponded to this period of soreness.

Komi and Buskirk (1972) conclude that although the eccentric exercise program increased muscle force, on the average, more than the concentric program, this type of exercise may not provide optimal muscle conditioning in the shortest period of time. They concluded this because their subjects experienced severe muscle soreness with an accompanying decline in force production in the early phase of conditioning. This conclusion provides support for the need for studies investigating the effects of exercise at equivalent power levels.

The results of our study cannot be directly related to Komi's study. Since Komi and Buskirk's subjects were performing maximal contractions they were not only assessing differences in contraction type but also differences in power levels. According to the force-velocity curve (Ellenbecker et al., 1988), the subjects performing maximal contractions in their eccentric conditioning group were probably producing more torque, and therefore more power, than their concentric group. Consequently, Komi and Buskirk were assessing the effect of a greater power level as well as contraction type in their study. In our study we were able to develop a protocol that allowed both of our subject groups to maintain a given level of power. Therefore, our results appear to reflect a difference based on contraction type alone. Interestingly, none of the subjects in our eccentric training group complained of soreness and none of these subjects had any difficulty in maintaining the required power levels.

Johnson et al. (1976) used a variation of the DeLorme technique to investigate the differences between concentric and eccentric exercise programs. One group exercised their elbow and knee flexors and extensors concentrically three times per week for six weeks at a load of 80% of a one repetition maximal concentric contraction (RM). Another group exercised the same muscle groups eccentrically for the same time period at 120% of a one RM. The authors measured force before and after the exercise program statically (using a cable tensiometer) and dynamically (using dumb-bells and a spring-loaded exerciser). Both exercise regimens resulted in significant gains in force production, however, these gains were not significantly different between groups.

The subjects in Johnson et al.'s study did not exercise at equivalent loads, did not perform the same number of repetitions per contraction type (the concentric group performed two sets of ten contractions and eccentric group two sets of six contractions), and did not exercise at consistent speeds of limb movement. This lack of control of their exercise variables makes it difficult to attribute contraction type dependent changes. We found a significant difference between our exercise groups with the concentric group improving significantly more than the eccentric group. A possible reason for the discrepancy between our study and Johnson et al. is that they attempted to provide their eccentric group with a near maximal load by using 120% of a one RM, whereas we controlled the power levels of each group so that they would be exercising at equivalent intensities.

Another possible reason for the difference between our results and those of Johnson et al. may be that they measured their subject's improvement in muscle performance using the same method in which they trained. According to Sale (1986) short periods of training may improve the subject's skill at performing the specific type of exercise. Johnson et al.'s subjects may have shown improvement due to a learning effect rather than a biological change. We attempted to eliminate the effects of learning in two ways. First, we obtained biopsy samples so that we could directly examine the effects of the exercise programs on fiber hypertrophy. Second, we examined the improvement in force production using isometric contractions which the subjects did not practice during the exercise period.

Studies conducted by Mannheimer (1969) and Ellenbecker (1988) both examined contraction type dependent exercise effects on muscle performance. In both of these studies the investigators compared subject groups performing maximal concentric or eccentric contractions. The number of repetitions and weeks of exercise was different for each study. Mannheimer reported that each group improved significantly in the ability to produce force but that these improvements were not different between groups. Ellenbecker reported significant gains in concentric and eccentric peak torque as a result of concentric training. He also found significant gains in concentric but not eccentric peak torque with eccentric training. Ellenbecker did not assess the difference in improvement between groups. Again the factors of learning and unequal exercise intensities are present in these two studies.

It seems clear that subjects participating in exercise programs consisting of maximal concentric or eccentric contractions can improve their ability to produce muscular force. Whether a program consisting of one type of maximal contraction is superior to another type is unclear. The evidence from these studies appears to show either a small or non-existent difference in improvement between exercise programs consisting of different contraction types. Many investigators assessed muscular improvement by using the same type of contraction that the subjects used during the training program. This may have clouded the issue of actual cellular changes with what might have been a learned skill enhancement. A further complication in these studies in the occurrence of exercise-induced DOMS (delayed-onset muscle soreness) in the eccentric training groups. It has been shown that this phenomenon is usually accompanied by a sharp decrease in the ability of subjects to produce muscular force. Therefore, subjects that were already exercising at different power levels may not have been training at consistent levels throughout the study.

We have attempted to provide a clear picture of contraction type dependent exercise effects by using a protocol that maintained a subject's power level at a constant level throughout the training program.

CONCLUSION

This report provides evidence that exercise programs consisting of eccentric contractions may result in less type II fiber hypertrophy than programs consisting of concentric contractions when subjects are exercising in an equivalent manner. Clinicians using these types of exercise programs should be aware that concentric contractions may be more effective not only in producing fiber hypertrophy but in the improvement of isometric torque by their patients. As with the majority of the literature examining contraction type dependent changes in skeletal muscle, this study used normal subjects. Future studies should investigate these relationships in relevant patient populations.

Table 1. Comparison of Percent Increase in Mean Fiber Area Between Exercise Groups

Group	Type I[a]	Type II[a]	Combined[b]
Concentric	14.67 ± 4.13	25.74 ± 6.37	20.20 ± 3.45
Eccentric	12.23 ± 4.45	17.80 ± 4.93	15.02 ± 4.14

[a] Percent increase in mean muscle fiber area between pre and post-exercise sessions with SD.

[b] Percent increase in combined type I and II mean muscle fiber area between pre and post-exercise sessions with SD.

Table 2. Comparison of Percent Increase in Mean Isometric Torque Between Exercise Groups

Group	Percent Increase[a]	SD
Concentric	16.09	8.2
Eccentric	8.27	5.1

[a] Percent increase in mean isometric torque between pre and post-exercise sessions.

Table 3. Summary Table: One-Way Between Subjects ANOVA, Percent Change in Combined Mean Fiber Areas Between Exercise Groups

Source	df	SS	MS	F[a]
Exercise Group	1	134.67	134.67	9.80[b]
Error	19	261.22	13.75	
Total	20	395.89		

[a] For $p < .01$, $F = 8.18$ for 1,19 df.
[b] Significant for $p < .01$.

Table 4. Summary Table: One-Way Between Subjects ANOVA, Percent Change in Mean Type I Fiber Area Between Exercise Groups

Source	df	SS	MS	F[a]
Exercise Group	1	29.78	29.78	1.71[b]
Error	19	331.35	17.44	
Total	20	361.13		

[a] For $p < .05$, $F = 4.38$ for 1,19 df.
[b] Not Significant for $p < .05$.

Table 5. Summary Table: One-Way Between Subjects ANOVA, Percent Change in Mean Type II Fiber Area Between Exercise Groups

Source	df	SS	MS	F[a]
Exercise Group	1	315.14	315.14	10.25[b]
Error	19	584.01	30.74	
Total	20	899.15		

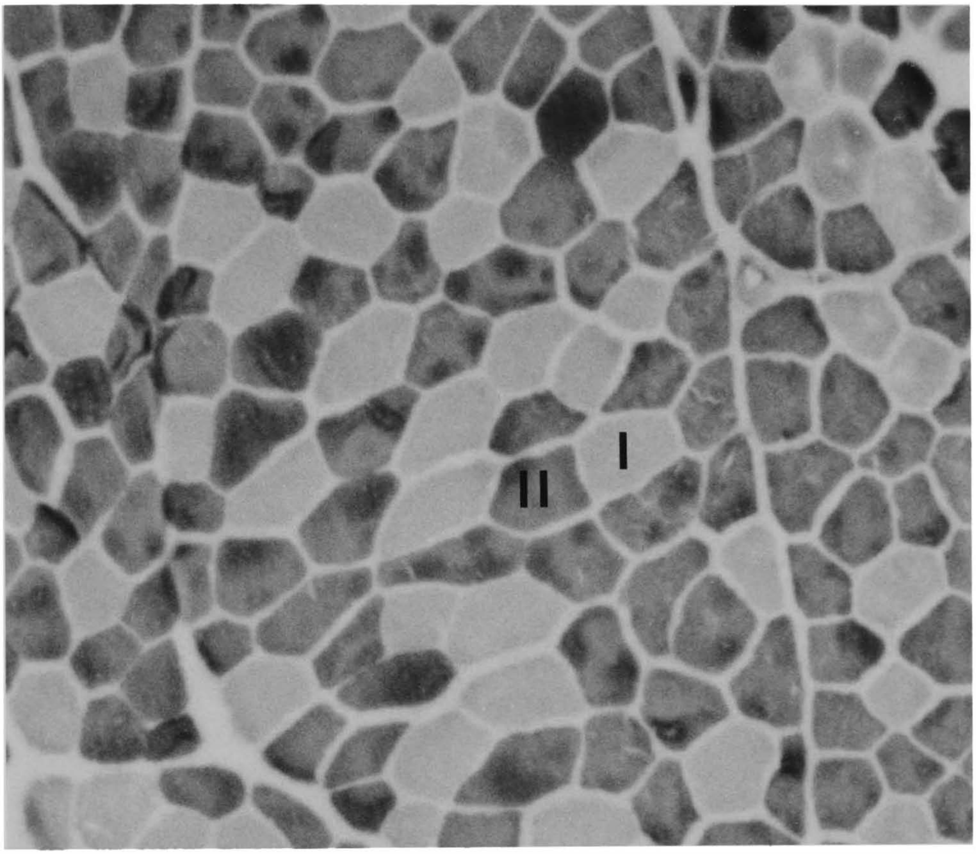
[a] For $p < .01$, $F = 8.18$ for 1,19 df.
[b] Significant for $p < .01$.

Table 6. Summary Table: One-Way Between Subjects ANOVA, Percent Change in Maximal Isometric Torque Between Exercise Groups

Source	df	SS	MS	F[a]
Exercise Group	1	305.61	305.61	6.87[b]
Error	19	845.31	44.49	
Total	20	1150.92		

[a] For $p < .05$, $F = 4.38$ for 1,19 df.
[b] Significant for $p < .05$.

Figure 1. Micrograph of muscle biopsy sample stained with myosin adenosine triphosphatase (ATPase) at a pH of 10.5. Fibers staining darkly were identified as type II, and fibers staining lightly were identified as type I. (x 40)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