To the Graduate Council:

I am submitting herewith a dissertation written by Lorna Ellen Swanson entitled "The Effects of Submaximal Eccentric Isokinetic Exercise on Strength and Power Changes and Indicators of Muscle Damage". I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Education.

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THE EFFECTS OF SUBMAXIMAL ECCENTRIC ISOKINETIC EXERCISE ON STRENGTH AND POWER CHANGES AND INDICATORS OF MUSCLE DAMAGE

A Dissertation
Presented for the
Doctor of Philosophy
Degree
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Lorna Ellen Swanson

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DEDICATION

To my parents, Marna and Hal Swanson

and

To my husband, Jim Kelley

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ABSTRACT

The purpose of this investigation was to examine the effects of submaximal eccentric isokinetic exercise on indicators of muscle damage, and to determine the optimal submaximal percentage at which eccentric isokinetic training should be performed to achieve strength and power gains in the quadriceps and hamstring muscles. The study was conducted in two parts. In Part I, 30 untrained subjects completed three sets of 15 eccentric contractions with the quadriceps and hamstrings using a Biodex isokinetic dynamometer. Subjects exercised at an intensity of 60%, 80% or 100% of their maximal eccentric peak torque, at a velocity of 60°/sec. Muscle soreness and other indicators of muscle damage including range of motion, maximal voluntary isometric strength and serum creatine kinase (CK) levels were measured before and 24, 48 and 72 hours after the exercise bout. The maximal exercise group experienced significant soreness in both muscle groups relative to the two submaximal groups at 48 and 72 hours post-exercise. In addition, decreased hamstring range of motion, decreased isometric strength in both muscle groups and increased serum CK levels were seen in the 100% group, but similar changes were not evident in either of the submaximal groups. No significant difference was found between the soreness response of the two muscle groups.

In Part II, 30 untrained volunteers underwent eight weeks of eccentric isokinetic training of the quadriceps and hamstrings at 60%, 80% or 100% of their maximal eccentric peak torque. Subjects performed three sets of 15 repetitions, three days per week, at a speed of 60°/sec. Ten subjects served as a control group and did not train. Eccentric peak torque at 30, 60, 90 and 120°/sec, concentric peak torque and average concentric power at 60, 180, 300

and 450°/sec, and a single leg hop for distance were measured before and after the training period.

Results showed that the eccentric peak torque of both muscle groups increased significantly in all training groups when tested at 60°/sec and 30°/sec, but the greatest improvements were seen in the 80% group. In the quadriceps, similar torque gains also occurred at the test speeds of 90°/sec and 120°/sec; however, only the 80% and 100% groups demonstrated carryover in eccentric hamstring torque gains to the higher velocities. The training effects did appear to be specific to the contraction mode. Concentric peak torque did not change in the 60% and 100% groups at any tested speed and only increased in the 80% group at the 60°/sec velocity. No significant increase in average power was seen in the quadriceps. The average power of the hamstrings increased in both the 80% and 100% groups, but not in the 60% group. No improvement in the single leg hop for distance occurred in any of the three training groups.

The results of this study indicate that eccentric isokinetic exercise training performed at 80% of maximal effort appears to be optimal for producing strength and power gains in the quadriceps and hamstrings while limiting the degree of muscle soreness and damage experienced after exercise.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Increased muscular strength is the primary goal of many training and rehabilitation programs. Clinically, isokinetic dynamometry is often used to facilitate progress toward this goal. Isokinetic exercise, as developed by Perrine in 1967, is a dynamic type of resisted exercise which features a pre-set fixed speed with resistance that is totally accommodating throughout the range of motion (90). If the force generated by the exercising limb results in an angular velocity that equals or exceeds the pre-set limit, the dynamometer produces a precise counterforce at each point in the range of motion so that the desired velocity is constantly maintained. Therefore, the contracting muscle can be maximally loaded throughout the entire range of motion.

Due to recent advances in isokinetic technology, current instrumentation now allows the performance and measurement of eccentric (lengthening) as well as concentric (shortening) muscle contractions. This is advantageous because most functional and athletic activities include both concentric and eccentric components, and it has been suggested that some muscle groups would respond better to eccentric training due to the nature of their functional use (3, 47, 67). Although there are many fundamental biomechanical and physiological differences between the two contraction types, the majority of the isokinetic research has focused only on concentric exercise. Until recently, investigation into the optimal use of eccentric isokinetic training has been limited, and knowledge of the effects of such training remains incomplete.

One consequence of eccentric muscle contraction is delayed onset muscle soreness (DOMS). This soreness, which begins approximately 24 hours after unaccustomed eccentric exercise, is accompanied by muscular stiffness and loss of range of motion, strength loss, elevations in muscle protein levels, such as creatine kinase, in the blood, and muscle fiber disruption (5, 19, 29, 48, 54, 55, 60, 63, 84, 120, 121, 122, 123, 125, 142, 160). Exercise induced muscle soreness has been shown to interfere with subsequent athletic performance (82, 158), and it may deter some individuals from continuing their training or rehabilitation programs. However, the amount of DOMS experienced is related not only to the contraction type, but also to the intensity of the exercise. Submaximal eccentric exercise may not always result in significant soreness (53, 167). Furthermore, the magnitude of the soreness response to submaximal exercise may not be identical in all muscle groups (57, 58).

Although most isokinetic research has concentrated on results achieved using maximal muscular contractions, maximal effort is not a feasible or desirable component of all rehabilitation programs. Cardiac complications, a need to protect healing soft tissue, or a desire to stress the oxidative energy system, would all rule out the use of maximal isokinetic contractions. In addition, Davies and Ellenbecker (32) advocate the use of submaximal exercise training because most functional activities of daily living are a series of submaximal contractions. Other clinical benefits of submaximal exercise, as stated by Davies (31), include reduction of pain through stimulation of mechano-receptors, reduction of neural dissociation, nourishment of articular cartilage, diminution of adhesion formation, an increase in soft tissue strength and specificity of fiber recruitment. Hald and Bottjen (81) have stated that the effects of this form of exercise certainly deserve investigation.

Maximal eccentric isokinetic training has been shown to produce both concentric and eccentric strength and power gains by some investigators, while others have found the gains to be mode-specific; although results appear to vary with the muscle group tested (9, 42, 47, 141, 171). None of the increases were velocity-specific to the training speed. Lacerte et al. (108) also demonstrated that the addition of a maximal eccentric component to a concentric isokinetic training program can result in greater eccentric and concentric torque gains than those achieved by training only with concentric contractions. However, there has been little investigation into the effects of submaximal eccentric training. Mayhew et al. (114) studied the effects of eccentric versus concentric training at 90% of maximal concentric power on muscle fiber hypertrophy, and found that concentric training was superior. Thiele et al. (165) performed an eccentric isokinetic training study using 50% and 75% of maximal eccentric isokinetic torque, but due to the limited training period, found no significant improvements with either of the training groups. Therefore, as Davies stated, "... there is a dire need for research to determine the optimal submaximal percentage of eccentric isokinetic training" (32).

The purpose of this study was to (1) determine if strength and power gains can be obtained during an 8 week submaximal eccentric isokinetic training program, (2) determine the optimal submaximal percentage of eccentric isokinetic training that will produce strength and power gains, yet minimize muscle damage and soreness, (3) determine the nature of any training-induced strength and power gains in terms of specificity of contraction mode and velocity, and (4) determine the difference in response, if any, between the two muscle groups tested.

The study was conducted in two parts. In part I, the effects of a single submaximal eccentric isokinetic exercise bout on indicators of muscle damage and delayed onset muscle soreness were investigated. In part II, the effects of an eight-week submaximal eccentric isokinetic training program were examined. Different subjects were used for each part of the study.

Hypotheses: Part I

In order to assess the effect of eccentric isokinetic exercise of the quadriceps femoris and hamstring muscles at selected percentages of maximal voluntary effort on indicators of muscle damage and delayed onset muscle soreness, the following hypotheses were tested:

Hypothesis 1:

During a 72 hour period following eccentric isokinetic exercise of the quadriceps femoris, the magnitude of perceived muscle soreness will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 2:

During a 72 hour period following eccentric isokinetic exercise of the hamstrings, the magnitude of perceived muscle soreness will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 3:

During the 72 hour period following eccentric isokinetic exercise of the quadriceps femoris, decreases in knee flexion range of motion will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 4:

During the 72 hour period following eccentric isokinetic exercise of the hamstrings, decreases in hamstring range of motion will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 5:

During the 72 hour period following eccentric isokinetic exercise of the quadriceps femoris, decrements in maximal isometric muscle strength will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 6:

During the 72 hour period following eccentric isokinetic exercise of the hamstrings, decrements in maximal isometric muscle strength will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 7:

During the 72 hour period following eccentric isokinetic exercise of the quadriceps femoris and hamstrings, elevation in serum creatine kinase concentration will differ between groups exercising at 60%, 80% and 100% of their maximal voluntary eccentric effort.

Hypothesis 8:

During the 72 hour period following maximal eccentric isokinetic exercise of the quadriceps femoris and hamstrings, the degree of perceived muscle soreness exhibited by the hamstrings will be greater than that exhibited by the quadriceps femoris.

Hypothesis 9:

During the 72 hour period following eccentric isokinetic exercise of the quadriceps femoris and hamstrings performed at 80% of maximal voluntary effort, the degree of perceived muscle soreness exhibited by the hamstrings will be greater than that exhibited by the quadriceps femoris.

Hypothesis 10:

During the 72 hour period following eccentric isokinetic exercise of the quadriceps femoris and hamstrings performed at 60% of maximal voluntary effort, the degree of perceived muscle soreness exhibited by the hamstrings will be greater than that exhibited by the quadriceps femoris.

Hypotheses: Part II

In order to assess the effects of eccentric isokinetic exercise training at selected percentages of maximal effort on strength gains in the quadriceps femoris and hamstring muscles, the following hypotheses were tested:

Hypothesis 1:

(A) Eight weeks of eccentric isokinetic training of the quadriceps femoris will result in an increase in eccentric peak torque at the training velocity (60^{o}/sec).

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 2:

(A) Eight weeks of eccentric isokinetic training of the hamstrings will result in an increase in eccentric peak torque at the training velocity (60^{o}/sec).

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 3:

(A) Eight weeks of eccentric isokinetic training of the quadriceps femoris at 60^{o}/sec will result in an increase in eccentric peak torque at other test velocities (30, 90 and 120^{o}/sec)

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 4:

(A) Eight weeks of eccentric isokinetic training of the hamstrings at 60°/sec will result in an increase in eccentric peak torque at other test velocities (30, 60 and 120°/sec).

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 5:

(A) Eight weeks of eccentric isokinetic training of the quadriceps femoris will result in an increase in concentric peak torque at selected test speeds.

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 6:

(A) Eight weeks of eccentric isokinetic training of the hamstrings will result in an increase in concentric peak torque at selected test speeds.

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 7:

(A) Eight weeks of eccentric isokinetic training of the quadriceps femoris will result in an increase in average concentric power at selected test speeds.

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 8:

(A) Eight weeks of eccentric isokinetic training of the hamstrings will result in an increase in average concentric power at selected test speeds.

(B) This increase will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Hypothesis 9:

(A) Eight weeks of eccentric isokinetic training of the quadriceps femoris and hamstrings will result in improvement in a functional single leg hop for distance test.

(B) This improvement will differ between groups training at 60%, 80% and 100% of maximal voluntary effort.

Delimitations of the Study

This study is delimited to:

1. Apparently healthy men and women between 18 and 40 years of age.
2. Persons with no history of knee surgery or serious pathology of the knee, quadriceps or hamstring muscles
3. Persons who have not been involved in lower extremity strength training for at least eight weeks prior to entering the study.
4. Persons whose eccentric peak torque production does not exceed the measurement capabilities of the dynamometer (300 foot pounds).

Limitations of the Study

This study is limited as follows:

1. The subjects will not be randomly selected, but recruited via posters, word of mouth and in cooperation with faculty offering class credit for participation in the study. However, there will be no intentional selection bias.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this review of literature will be to: (1) define eccentric and concentric contractions and elucidate the biomechanical and physiological differences between the two contraction modes, (2) discuss possible mechanisms of delayed onset muscle soreness and describe the components of its concomitant muscle damage, (3) discuss the functional relevance of eccentric exercise training as it relates to the biomechanical patterns of the hamstrings and quadriceps femoris muscles, (4) present research which examines the muscular response to eccentric exercise training, and (5) discuss studies which investigate the specificity of concentric and eccentric isokinetic exercise in terms of contraction mode and training velocity.

Definitions

A concentric muscle contraction is one in which a muscle exerts force by developing tension and shortening against an opposing force. The contractile component of the muscle (myofibrils) shortens, and tension on the tendon increases. When the force exerted by the muscle exceeds that produced by the resistance, the resistance is lifted by further shortening of the myofibrils. External work is produced. Conversely, during an eccentric contraction, a muscle exerts force by developing tension and controlling its lengthening in the direction of the opposing force (33). Elongation of the muscle is controlled by an active contraction of the myofibrils and a passive resistance to stretch by the non-contractile tissue (tendon, connective tissue sheaths and sarcolemma). Because the non-contractile tissue contributes to the muscle's total force production, less tension must be produced by the contractile component of the muscle than that required during a concentric contraction against equal resistance. By lengthening while resisting an external force, the muscle absorbs and stores mechanical energy.

Biomechanical and Physiological Differences Between Contraction Modes

Past research has demonstrated that there are several fundamental differences between concentric and eccentric muscle contractions. These include:

(I) At the same velocity, an eccentric contraction generates a greater maximal force than does a concentric contraction (23, 39, 76, 77, 89, 134, 138, 140, 155). This relationship was expanded by Elftman (46) to include isometric contractions. The Elftman proposal states that the predictable hierarchy of optimal muscle force production is Eccentric > Isometric > Concentric. This relationship holds true for all muscle groups.

(II) At a given force, contractile components generate less tension during eccentric contractions than during concentric contractions (33). The increased force generated during an eccentric contraction is a result of non-contractile tissue working together with the contractile elements.

(III) At the same resistance, electromyographic (EMG) activity is lower during an eccentric contraction, meaning that fewer motor units are recruited during an eccentric contraction to produce the same force as in a concentric contraction (6, 97, 105, 106, 122, 164). Therefore, greater tension is developed per active sarcomere in an eccentric contraction. However, EMG activity has been shown to rise progressively during a prolonged bout of submaximal eccentric exercise (36). Armstrong (5) suggested the increase was indicative of damage to the motor units initially recruited, thus resulting in the need for additional fiber recruitment to maintain the desired force.

(IV) The mechanical efficiency of eccentric contractions is higher than that of concentric contractions (106). Concentric contractions have a net efficiency (mechanical work: energy expenditure) of 13 to 26% as compared to the 85 to 120% seen in eccentric actions (51).

(V) At comparable work loads, the metabolic energy cost for eccentric contractions is considerably lower than for concentric contractions (104, 145). The relative difference in oxygen consumption becomes more pronounced as the intensity of the exercise increases (49).

(VI) Similarly, other physiological responses such as cardiac output, muscle blood flow and lactate production are lower during eccentric exercise (5, 103, 146).

(VII) The rating of perceived exertion (RPE) is usually lower for eccentric exercise at equivalent work rates, than for concentric exercise (88). Eccentric contractions are said to be performed with greater ease and less discomfort than concentric contractions (95). However, the RPE is reported to be higher for eccentric contraction velocities below 30°/sec than for those performed at higher velocities (4).

(VIII) The electrochemical delay (elapsed time from biochemical response to the actual onset of muscular tension) is shorter for eccentric contractions than for concentric contractions (15).

(IX) As the contraction velocity increases, there is a significant decrease in concentric force, whereas eccentric force either increases, stays constant or decreases slightly (5, 23, 27, 71, 72, 77, 79, 103, 140, 146, 173, 175, 176). Although the force-velocity relationship is well established for concentric muscle loading, the eccentric force-velocity relationship remains controversial. Variables to be considered are the contraction type (isotonic or isokinetic) and the speeds of contraction that are employed (3).

(X) Post-exercise muscular pain and tenderness (DOMS) are associated with eccentric training, but do not occur after concentric contractions (5, 18, 54, 55, 98, 105, 123, 125, 145, 163).

Delayed Onset Muscle Soreness and Indicators of Muscle Damage

Delayed onset muscle soreness is the sensation of discomfort or pain in the skeletal muscles that occurs after unaccustomed muscular exertion, especially that which contains an eccentric component. It is not associated with concentric-only exercise (18, 163). DOMS is characterized by discomfort that begins several hours after exercise and peaks after 24 to 72 hours; however, soreness can last for seven to ten days. The magnitude of DOMS can range from severe pain and stiffness which interferes with normal muscular function, to only a slight sensation of tenderness felt in response to external pressure or placing the muscle on a stretch. Indicators of muscle damage that accompany DOMS include structural changes in the muscle fibers, increased muscle enzymes, such as creatine kinase in the blood, loss of range of motion, and decreased muscular strength. Although DOMS is a common phenomenon, about which there is a great deal of information, its precise underlying mechanism remains unclear.

Current Hypotheses Regarding the Mechanism of DOMS

Current hypotheses concerning the cause of DOMS center around sequelae of mechanical damage to the muscle fibers and the surrounding connective tissue as a result of the high level of tension generated during an eccentric contraction. The torn tissue hypothesis attributes the soreness to ultrastructural damage to the muscle fibers, and is supported by muscle biopsy studies which describe disruption of subcellular components such as the Z-band, Z-disc, and sarcoplasmic reticulum (59, 60, 61, 64, 160).

The torn connective tissue hypothesis ascribes the pain to selective damage of the connective tissue components of the muscle such as the epimysium, perimysium, endomysium, fascia and tendons. It is given credence by the work of Abraham (1, 2), who reported increased hydroxyproline (a marker of connective tissue damage) in the urine after subjects performed eccentric exercise. These increases coincided with reports of peak soreness by the subjects. Furthermore, DOMS is most prevalent in areas that have a high concentration of connective tissue (105).

Muscle swelling and inflammation have also been suggested as mechanisms for DOMS. Stauber et al. (160) proposed that "myofiber disruption allows intracellular proteins to escape and extracellular proteins and ions to enter, causing swelling, whereas the disrupted extracellular matrix initiates the inflammatory response". The proposal was based, in part, on a release of mast cells seen 48 hours after exercise. Smith (157) also points out evidence of cellular infiltrates, increased lysosomal activity and histological changes that are typically seen in acute inflammation. While these authors agree that mechanical damage to the muscle fibers instigates the process that results in DOMS, they argue that the time course of the pain and inflammation is different than the indicators of myofiber damage. Therefore, the sequelae that follow the injury may be more important in explaining the symptoms than the mechanical damage itself.

Anatomical Site of DOMS

Delayed onset muscle soreness has been reported in many different muscle groups after unaccustomed eccentric exercise. Usually, the pain and tenderness is most evident in the distal portion of the muscle, in the area of the musculotendinous junction, and in those areas of the muscle which contain the greatest amount of connective tissue (5, 60, 64, 105, 125). It is not known if this is because pain receptors are more concentrated in the tendons and connective tissue of the muscles, if the damage is localized to these regions, or if it is a combination of the two factors. However, the distribution of soreness is most likely affected by the intensity, duration and type of eccentric exercise (120, 167) In severe DOMS, the pain is generalized throughout most of the muscle belly (5, 63). Geisler and Hackney (70) found two distinct groups of soreness responses following identical eccentric exercise of the biceps brachii. Five subjects reported soreness in the mid muscle belly, and the other five at the musculotendinous junction. Interestingly, creatine kinase levels for subjects with pain at the junction were higher than for those who experienced soreness in the muscle belly. In contrast, Newham (120) found pain and tenderness over the entire biceps brachii after a similar exercise bout. Friden et al. (63) described marked soreness of the entire muscle belly following eccentric exercise of the ankle dorsiflexors, although the most pronounced symptoms were referred to the distal portion.

After eccentric exercise of the quadriceps, several investigators (45, 84, 85, 122, 125) have reported that tenderness was most intense at the distal, medial portion of the thigh, just above the knee (vastus medialis), and at the proximal, lateral thigh. The central region (rectus femoris) was generally spared except after very intense exercise when the tenderness became more diffuse. Hasson et al. (83) estimated that 40 to 50% of the quadriceps muscle became tender after an intense eccentric exercise bout, and Friden et al. (64) reported pain and tenderness over the entire quadriceps after eccentric cycling. To date, there are no published reports concerning the distribution of muscle soreness in the hamstring muscles.

Structural Changes

Significant structural changes have been reported in muscles affected by exercise-induced muscle soreness. They include disruption of the sarcolemma, swelling or disruption of the sarcotubular system, distortion of the contractile components of the myofibrils, cytoskeletal damage, and abnormalities of the extracellular myofiber matrix (61). Friden (60) states that the most prominent finding is disruption of the contractile material, especially the Z-band, of the myofibrils. The normally well-organized Z-bands had a ragged, zigzag appearance, and damage included streaming, broadening or even total disruption (60, 61). It is not known if changes in the Z-bands are a direct result of the high fiber tension generated during an eccentric contraction, or if they are due to changes in the sarcoplasmic reticulum which lead to calcium induced Z-band damage. Although disturbances were found in both Type I and Type II muscle fibers, they were more prevalent in the Type II fibers by a three to one ratio (61).

Stauber et al. (160) performed histological studies that also revealed widened perimysial areas between fascicles, and separation of myofibers from one another within the fascicles. Mast cell degranulation was evident in sections from all subjects and was primarily found in the perimysial area and near blood vessels.

Newham et al. (124) used electron microscopy to examine muscle biopsies taken just prior to, and 24 to 48 hours after a 20 minute step test. No morphological abnormalities were seen in any of the samples taken from the leg that performed the concentric portion of the exercise, but damage similar to that described by Friden was seen in samples from the leg that performed the eccentric contractions. The abnormalities were more focal in nature immediately after cessation of the exercise bout, but were more extensive in the muscle samples taken one to two days later. These samples exhibited extensive damage in 51% of the muscle fibers examined. The damage was essentially the same as that seen immediately after exercise, but it had developed to involve more sarcomeres. Fewer localized areas and more widespread areas were observed.

Evidence of structural muscle damage can also be seen with magnetic resonance imaging (MRI) (150, 151). Serial MRI revealed a statistically significant increase in T-2 relaxation times following performance of eccentric exercise. This increase, which is determined by the use of T-2 weighted MR images, is indicative of muscular damage. Relaxation times peaked three to five days after exercise, but subclinical abnormalities were observed for as long as 75 days. No change was seen following concentric exercise.

Enzyme Changes

Disruption and damage to muscle and connective tissue produce a pronounced enzyme efflux into the extracellular space. This phenomenon may be caused by altered membrane permeability or fiber degeneration, and can involve creatine kinase (CK), hydroxyproline (OHP), or myoglobin. Of these, creatine kinase is the most commonly studied. Although it has a different time course than delayed onset muscle pain and thus, cannot be said to cause soreness, CK is often used as an indicator of muscle damage (18, 19, 57, 58, 63, 70, 107, 120, 121, 123, 129, 130, 137, 144, 145, 174). It is produced in proportion to the intensity and duration of the exercise causing the damage and is less pronounced in females (152). However, there is also considerable individual variation in CK response which is independent of gender, fitness level or body composition (19, 122, 126). Clarkson et al. (19) described three groups of CK responders; high, medium and low. The normal range of serum and plasma CK values for healthy persons who have not recently participated in strenuous exercise is 15-110 IU/L for males and 15-90 IU/L for females (153).

There is some disagreement about the extent of CK efflux after various contraction modes. Clarkson et al. (18) measured CK values prior to, and up to 25 hours after, subjects completed six sets of ten isometric, concentric or eccentric contractions of the biceps brachii. In order to equate the work performed, the eccentric contractions were performed using a resistance equal to 100% of the subject's concentric 1-RM. All three groups demonstrated a small, but significant CK increase (around 35%); however, there was no difference between the three responses. In contrast, Friden et al. (63) reported a 36% increase in CK levels, to 201 IU/L, 48 hours after eccentric ankle dorsiflexion, but found no change after either isometric or concentric contractions of the same muscle group. Other investigators (123, 144, 145) have examined CK changes after level, uphill and downhill running. They found significant CK increases following downhill running, during which muscles perform principally eccentric contractions; however little change was elicited by level or uphill running, during which concentric contractions are dominant. In the investigation by Newham et al. (123), plasma CK values were elevated by as much as 15,000 IU/L four to seven days after the downhill run.

An efflux of creatine kinase has also been reported after stepping exercise (84, 122, 126). Newham et al. (122) found an early rise in plasma CK levels, but also discovered a greater delayed increase in about half of their subjects of up to 34,500 IU/L. Peak values did not appear until the fourth or fifth day after exercise. All subjects who demonstrated the delayed CK rise also exhibited muscle tenderness; however, some were tender without demonstrating the large delayed response. In those who did exhibit the delayed response, tenderness was decreasing as CK was peaking. The authors suggested that a pain producing substance might be acting as a precursor for the subsequent enzyme release.

Similar increases in creatine kinase have been reported after eccentric exercise of a specific muscle group. Clarkson et al. (19) obtained CK measurements for ten days following high force eccentric exercise of the biceps brachii and found levels up to 2,500 IU/L on day four. This is considerably higher than the increases reported in a previous study by Clarkson (18) using a similar apparatus. However, in that study, blood sample collections ceased 25 hours after the exercise bout. The values at the one day point are similar in both studies (around 200 IU/L). Again, the substantially higher values appeared much later.

Franklin et al. (57, 58) examined the creatine kinase response to isokinetic exercise of the quadriceps femoris and the hamstrings. In their first study, (57) subjects exercised both muscle groups by performing three sets of 35 eccentric or concentric contractions at 80% of their respective concentric peak torque. The mean CK levels were 14,856 IU/L for the eccentric group and 360 IU/L for the concentric group, at 72 hours post exercise. In a subsequent study (58), when subjects performed an identical eccentric exercise bout, using only one of the two muscle groups, mean CK levels 72 hours post exercise were 6,037 IU/L for the group who exercised their hamstrings and 261 IU/L for those who exercised their quadriceps. In both investigations, subjects reported a significantly greater degree of soreness in the hamstrings than in the quadriceps muscles. Kulig et al. (107) also examined CK levels after eccentric isokinetic hamstring exercise; however, blood samples were only drawn for a 48 hour period. They stated that CK levels increased significantly in all 26 subjects, but specific levels were not reported.

Creatine kinase levels have also been ascertained after performance of specific sports activity. Pitching requires significant eccentric contractions of the posterior shoulder muscles to decelerate the arm as the ball is released; therefore, Potteiger et al. (137) evaluated the CK response in baseball pitchers after three simulated games. A mild CK elevation (around 245 IU/L) occurred 24 hours after each game, but levels approached baseline by 72 hours.

As stated earlier, Abraham (1) described an increase in urinary hydroxyproline (OHP) 48 hours after a bout of eccentric exercise. OHP has been justified as a specific marker for connective tissue breakdown because it is found primarily in collagen and is not thought to be recycled or metabolized when released after collagen degradation (91). An increase in OHP excretion which is concurrent with the appearance of muscle soreness could suggest connective tissue disruption. However, other investigators have failed to support Abraham's findings. Gissal (73) used a similar bench stepping activity to induce soreness, but failed to detect an increase in OHP excretion. Geisler and Hackney (70) found no change in OHP excretion up to 72 hours after subjects had performed 60 eccentric bicep curls. Horswill et al. (91) found no significant increases in OHP after intense weight-training of nine muscle groups, although this exercise produced soreness in a considerably greater muscle mass than did the stepping exercise employed by Abraham. Therefore, although connective tissue damage is thought to occur as a result of soreness-producing exercise, hydroxyproline does not appear to be a reliable marker of this damage.

Range of Motion Changes

A feeling of stiffness, evident during attempts to stretch the affected muscle group, is a common symptom of exercise-induced muscle damage. For example, after damage to the calf muscle, the involved limb is held in a flexed posture, and subjects reported difficulty straightening their knees when rising from a sitting position (123). After stepping exercise which involves the quadriceps femoris and gluteal muscles, subjects found it hard to bend sufficiently to put on their shoes in the morning (122).

In a comparison of subjective and objective measures of DOMS in the hamstrings, Weiss et al. (174) found that range of motion provides a good objective evaluation of the severity of muscle soreness. Both soreness and the decrease in motion peaked 48 hours after exercise, reached minimal values on day five, but did not return to the pre-exercise level during the time course of the study. The correlation between range of motion and soreness scores was 0.91.

Several investigators (19, 34, 37, 44, 54, 55, 92, 94, 98, 132, 151, 181) have reported decreased range of motion at the elbow after they induced DOMS in the biceps brachii. Flexion contractures of up to 20 degrees were evident immediately after exercise, and they continued to increase until reaching a peak at 48 hours. Attempts to forcibly extend the elbow elicited a painful response. Yackzan et al. (181) reported a 36.4% loss of active extension range of motion at 48 hours post exercise. They also found a significant negative correlation between soreness and range of motion scores.

All investigators stated that range of motion returned to normal within seven to ten days.

Jones et al. (98) and Howell et al. (92) conducted similar studies in which they measured the electrical activity in the biceps brachii during the period of decreased range of motion. They both determined that loss of range of motion was not accompanied by an increase in EMG activity. These findings eliminated muscle fiber activation by the motor neuron as a cause of the muscle shortening, thus discounting an earlier theory by DeVries (35) who believed that the pain and tenderness of DOMS was caused by reflex induced, sustained electrical activity of localized motor units. Other explanations for the decreased range of motion have since been proposed. First, shortened non-contractile elements, acting in parallel with the muscle fibers, could contribute to the loss of motion. These structures are damaged during the eccentric exercise bout, and pain during attempts to stretch the muscle is clearly related to the resultant mechanical stiffness. The subsequent increases in soreness and muscle shortening follow the same time course and appear to be a secondary reaction to the tissue damage. Edema may also develop within the connective tissue network or the tendinous attachments.

Ebbeling and Clarkson (43) postulated that the decreased motion could be due to an abnormal accumulation of calcium inside the muscle cell. The forces produced during eccentric exercise can cause damage to the sarcolemma and/or alter the permeability of the cell membrane. The resulting influx of calcium has been shown to produce contractures, as well as activate a calcium-dependent proteolytic enzyme that degrades the Z- bands (5, 132).

Smith suggested that the reduced range of motion, which corresponds with peak muscle soreness, may place the involved muscles in a position optimal for healing (157). Her idea is supported by Clancy and Clarkson (17) who enhanced muscle recovery by using a sling to immobilize the involved muscles in a shortened position during the 72 hours after soreness-inducing exercise.

Strength Decrements

Impairment of muscular function is a significant component of DOMS, and has been documented in several muscle groups (19, 22, 29, 37, 38, 44, 54, 55, 74, 75, 85, 121, 125, 132, 142, 183). A sensation of profound weakness is commonly reported immediately after a novel bout of eccentric exercise. Although the weakness is transient, it persists for several days and can impede performance level in subsequent exercise sessions. Colliander and Tesch (22) demonstrated that eccentric, not concentric, contractions result in muscular impairment by measuring dynamic peak torque before and after subjects performed 50 eccentric or concentric contractions of the quadriceps. The concentric group exhibited a decrease in concentric peak torque immediately after the exercise bout, but made a full recovery within 30 minutes. Eccentric peak torque was unaffected. In contrast, both eccentric and concentric peak torque decreased significantly in the eccentric group, with no subsequent recovery.

The degree to which impairment occurs appears to vary according to muscle group and type of eccentric exercise performed. Several authors (19, 37, 44, 54, 55, 121, 132, 183) have described a severe force decrement in the biceps brachii following exhaustive eccentric arm curls. Immediately after the exercise bouts, isometric strength was decreased by at least 50%. A gradual return of strength ensued, however, full recovery was not achieved after 14 days. Isokinetic torque also declined at all speeds and remained significantly lower for at least seven days. The duration of strength loss far exceeded the period of muscle soreness.

Although muscle strength does decrease significantly after bench stepping and downhill running, the magnitude of the decline is reported as being less than that seen after arm exercise, and a full recovery is achieved in 72 hours (37, 85, 125). However, Sargent and Dolan (142) do report a progressive 65% drop in both force and power output after subjects walked downhill until they collapsed from muscle weakness.

Golden and Dudley (74) investigated isotonic and isokinetic strength of the quadriceps after subjects performed ten sets of eccentric contractions at 85% of their one repetition maximum (1-RM). The eccentric and concentric 1-RM were 32% lower after 24 hours. By day seven, the eccentric 1-RM returned to baseline, but the concentric 1-RM had not recovered by day ten. The angle specific isokinetic peak torque decreased in a similar manner, and concentric recovery was not complete ten days later, thus confirming that recovery was more prolonged for concentric contractions. The investigators postulated that voluntary activation of the quadriceps is maximal during concentric contractions, whereas all available motor units are not recruited during maximal eccentric contractions. Therefore during recovery, subjects may have learned to activate motor units not usually recruited in order to regain baseline performance.

To ascertain whether the force decrements which accompany DOMS are due to inherent muscle damage or a reluctance to voluntarily contract the sore muscles, Clarkson et al. (19), Davies and White (29), and Newham et al. (121, 125) compared voluntary contraction force to contraction force elicited by electrical stimulation of the specified muscle group. They found that all subjects produced their maximal force voluntarily in spite of the muscle soreness. The maximal twitch and tetanic tensions were substantially reduced for a prolonged period (29, 125). In addition, researchers observed that strength deficits began before soreness was evident and remained after it had ceased, further eliminating a cause and effect relationship.

Although the specific cause of the muscle weakness seen after eccentric exercise is not known, it is generally felt that muscle fiber damage plays an important role. Davies and White (29) suggest that repeated eccentric contractions damage the contractile protein and affect the cycling of cross bridges within the muscle fiber. Clarkson (19) hypothesized that stretching of the sarcomeres results in a reduced overlap between the actin and myosin filaments, thereby reducing the maximal number of cross bridges that could form. More research is needed to determine the specific mechanism involved.

Functional Relevance of Eccentric Training of the Quadriceps Femoris and Hamstring Muscles

Both the quadriceps femoris and the hamstring muscles exhibit a significant eccentric component in functional activities such as walking, as well as in athletic endeavors such as running. In order to understand the eccentric contribution of these muscle groups, one must first have a basic knowledge of the gait cycle for walking and running.

The walking gait cycle is composed of two phases, stance phase (60%) and swing phase (40%). The stance phase of gait consists of heel strike, foot flat and toe off. The swing phase is the period from toe off to heel strike. One complete gait cycle is considered to be from heel strike to heel strike of the same leg, and one lower extremity is always in contact with the ground (179). The running cycle also has two phases, the support phase (foot strike, mid-support and take off) and the recovery or float phase (follow through, forward swing and foot descent) (156). The float phase involves a complete absence of ground contact. As running speed increases, less time is spent in the support phase, and the length of the float phase increases.

During walking, the quadriceps first contract concentrically to hold the knee in full extension during heel strike. The knee then flexes to 15 degrees during foot flat, and the stance leg is required to bear weight on a partially flexed knee. Therefore, the quadriceps must begin contracting eccentrically to control this knee flexion because the center of gravity now falls behind the axis of the knee joint (12). The knee will buckle without this eccentric control. Little or no quadriceps activity is required during midstance, but the quadriceps must again control knee flexion by contracting eccentrically as the knee flexes to 40 degrees by toe off.

The hamstrings exhibit their greatest eccentric activity during the swing phase of walking gait. As the leg swings forward, the hamstring muscles simultaneously lengthen over the hip and the knee as their muscle tension increases. They function to decelerate the forward swing of the leg thus preventing excessive hip flexion, and controlling the knee extension brought about by the quadriceps muscles. As a result, hip flexion is limited to 30 degrees, and knee extension is smooth, rather than abrupt. The hamstrings are also active in the early stance phase of gait. At heel strike, they provide stability and initiate flexion of the knee. From heel strike to foot flat, they contract eccentrically to assist the gluteus maximus in counteracting the hip flexion moment thus preventing excessive anterior pelvic tilt and extreme hip flexion (128).

During running, the quadriceps and especially the hamstrings have an even greater eccentric contribution. At some point during each running stride cycle, the quadriceps and hamstrings contract eccentrically to decelerate the body's center of mass in the vertical plane. This is true in level running and is accentuated during downhill running because a relatively greater degree of lowering of the center of mass is required (145). The quadriceps act as much to limit knee flexion following foot strike as they do to power knee extension, and likewise, the hamstrings function more to decelerate knee extension during running than they do to initiate knee flexion.

Montgomery et al. (118) conducted an electromyographic (EMG) analysis to determine the firing patterns of the hip and knee musculature during running. Indwelling EMG electrodes were placed in 11 different muscles of the hip and knee of 30 runners in order to record muscle activity. As they ran, subjects were also filmed at a speed of 100 frames per second. Results showed that of the quadriceps muscles, the vastus intermedius and the rectus femoris muscles demonstrate the highest level of eccentric action. The vastus intermedius eccentrically controls knee flexion throughout the forward swing phase and is assisted by the rectus femoris. The rectus femoris also assists with eccentric control of hip extension during early forward swing, as well as aiding the eccentric control of knee extension during late forward swing. In the hamstring muscle group, the long head of the biceps femoris and the semimembranosus were found to exhibit the greatest eccentric action during middle forward swing, as they function to control hip flexion. The short head of the biceps femoris was found to provide the greatest eccentric activity during the late forward swing phase as it decelerates knee extension. The authors reported that faster running paces led to increased activity in the active muscles, and hypothesized that this increase may lead to injury in the muscles that were contracting eccentrically because they must withstand a more rapid and severe lengthening.

Several other researchers (25, 112, 156, 159, 179) have also reported on hamstring function during sprinting. They all describe eccentric contraction as beginning during the latter part of the forward swing phase in order to decelerate knee extension and hip flexion. Knee motion is terminated 30 degrees short of terminal knee extension. At this point, the hamstrings are at their greatest length, thus generating maximal tension. At the point when the foot makes contact with the ground, they switch from maximal eccentric to concentric force production to stabilize the knee in preparation for the support phase. Stanton and Purdam (159), quoting Wood et al., reported that hamstring peak torque values are typically 150 Nm at the knee and 250 Nm at the hip at late swing phase in order to control the momentum of the leg in preparation for foot strike. Mann and Sprague (112) also studied force production of the lower extremity muscles in 15 collegiate and world class sprinters. They used a force platform to record horizontal and vertical component forces. The hamstring muscles developed the greatest force of any lower extremity muscles at the moment of ground contact.

The required increase in eccentric muscle activity in the late forward swing phase of running appears to be related to hamstring injury. This is especially true during transition into the competitive portion of the athletic season because a greater emphasis is placed on speed during training. As running speed increases, the hamstrings must contract faster and absorb more force during a shorter period of time (111). Since a muscle's ability to absorb force is directly proportional to both its passive and active components (69), one would assume that a stronger hamstring muscle would absorb more force, and thus be less susceptible to injury. Cavagna et al. (14) found that the contractile component of a muscle plays a progressively smaller role in the absorption of forces with increased running speed as compared to the contribution of the connective tissue component. Therefore, eccentric training of the hamstrings may progressively increase strength in the connective tissue components of the muscle so that they might better withstand the high forces encountered during maximal speeds. Conversely, attempts at high speed sprinting with unconditioned muscles may result in pathological eccentric force production and hamstring injury due the muscle's inability to withstand the forces needed to decelerate the leg.

Muscle weakness is often cited as a factor that predisposes one to injury based on the muscle's role as an energy absorbing structure (127). However, there is disagreement in the literature as to whether muscle weakness is an important causative factor in hamstring strains. Worrell et al. (180) compared isokinetic hamstring strength in athletes with a history of hamstring injury to those who were uninjured. All athletes participated in sports classified as placing them at a high risk for hamstring injury. The injured group did not include athletes currently receiving rehabilitation. No difference was found in the concentric or the eccentric hamstring peak torque at velocities of 60 and 180°/sec. The authors stated that hamstring flexibility, not hamstring strength, was the most important component of injury prevention. However, Jonhagen et al. (99) compared hamstring strength in 11 sprinters with recent hamstring injuries to that of uninjured sprinters. Both eccentric and concentric peak torque were measured in the quadriceps and hamstrings at eccentric speeds of 30, 60 and 230°/sec and concentric speeds of 30, 180 and 270°/sec. The uninjured sprinters had significantly higher eccentric hamstring torques at all velocities, with the most marked differences being seen at the high velocities. There was no difference between the two groups in concentric torques except in the quadriceps at the slowest velocity. The authors concluded that the high predilection for recurrent hamstring injuries could be related to decreased eccentric hamstring strength, especially at high velocities. Stanton and Purdam (159) measured isokinetic knee flexion torques in injured runners at 180°/sec using similar hip and knee angles to those occurring at the end of the forward swing phase of running. They reported a characteristic deficit in knee flexion torques before, during and immediately after the "eccentric-concentric turnaround" required at this part of the running gait cycle. More research is needed to further clarify the relationship between muscle weakness and/or muscle imbalances and the predilection to hamstring injury.

An inability to generate high levels of peak eccentric hamstring torque at the moment just prior to foot strike has been found to limit running speed by limiting how late in the recovery phase the runner can begin to decelerate the leg (16). As a result, the runner is unable to increase speed by increasing the stride frequency. Improvement in eccentric hamstring strength gives the athlete the potential to decrease the time spent in the recovery phase, thus permitting an increase in their cadence. Therefore, the ability to produce high eccentric force just before and during foot strike appears to be related to the quality of athletic performance.

Specificity is an important consideration in all training regimens. If a muscle is required to produce high intensities and high speeds, it must be trained under similar conditions. Eccentric contractions, especially those done at higher velocities, provide this ability. Furthermore, the hamstring muscles have a preponderance of Type II muscle fibers (67, 68). Garrett et al. (67) found the mean proportion of Type II fibers to be above 50% in seven hamstring biopsy sites. Type II fibers, which have faster contraction times, are less fatigue resistant, generate more force per unit of cross-sectional area, and are selectively recruited by eccentric contractions. Therefore, progressive lower extremity eccentric exercise is advocated by many authors as a necessary component of training for both competitive and recreational athletes (118, 159, 179).

Muscular Responses to Eccentric Exercise Training

Some of the earlier investigations into the possible benefits of employing eccentric contractions as part of a training program designed to enhance strength gains were conducted by Johnson and colleagues (95, 96, 97). They did a series of studies comparing eccentric and concentric training, and concluded that both were equally effective in evoking strength gains. In his first study, Johnson (95) trained nine male college students using either isotonic-concentric or isotonic-eccentric contractions; bench press and leg extension exercises were performed. All nine subjects did concentric leg extensions with one leg and eccentric leg extensions with the opposite leg. However for the bench press, the original group was subdivided into two smaller groups. Four subjects performed only the concentric portion of the press, while the other five used only eccentric contractions to perform what the author termed a "bench repress". All subjects trained three times per week for eight weeks. Ten repetitions of each exercise were completed during all training sessions using 80% of the subject's 1-RM. Results showed that both contraction types elicited significant gains in strength for both the upper and lower extremities as demonstrated by an increase in the 1-RM after training. Neither training program was found to be superior to the other, and changes recorded week to week also followed a similar course. However, there was a greater perceived ease of training when subjects executed the eccentric as opposed to the concentric contractions.

Johnson and Adamczyk (96) studied static and dynamic strength gains in a group of medical students by employing a variety of isotonic exercises. These exercises had an eccentric and concentric component on one side, but only a concentric component on the contralateral side. Results showed that changes in static strength were inconsistent in the various muscle groups. Increases in static shoulder flexion and knee flexion strength were seen in both the concentrically and concentrically-eccentrically trained muscles, but no increases in static strength were seen in three other tested muscle groups. Dynamically, significant strength gains were made in all tests. The mean strength gains in the limb that experienced additional eccentric training were greater than those seen in the limb that trained only concentrically, but this difference did not reach significance.

Johnson et al. (97) conducted an investigation similar to the earlier study by Johnson (95) but required subjects to perform concentric contractions against a resistance equal to 80% of their 1-RM and eccentric contractions against a force of 120% of their 1-RM. All exercises in this study were unilateral in design, so that all subjects trained the limbs on one side of the body using concentric contractions, while those on the opposite side performed eccentric contractions. Subjects completed two sets of ten concentric contractions, but only two sets of six eccentric contractions were required. The authors hypothesized that a load closer to maximal eccentric effort would result in greater strength gains. However, although both groups achieved significant strength gains both statically and dynamically, there was no significant difference in gains between the two contraction types. The design of this study was criticized by later authors (41) because bilateral comparison of limbs on the same subject is confounded by the fact that unilateral training increases the strength of the contralateral limb.

Mannheimer (113) reported similar results in his study comparing strength gains in subjects who performed eccentric versus concentric triceps exercises for a period of 30 days. An overall mean gain of 22.1% was achieved by those performing eccentric contractions, as compared to a 19.2% gain by those who exercised concentrically. However, the time course of the improvements did differ between the two groups. The eccentric group demonstrated a significantly greater gain (19.8%) after the first 19 days of the of the program, but showed a much smaller improvement (1.1% and 1.2%) during two subsequent retests. The concentric group demonstrated a more consistent improvement pattern (7.6%, 7.7%, 3.9%) throughout the training period. The author suggested that the eccentric group may have resumed their strength increase if the exercise period had lasted beyond the time limits of this study. He further recommended use of eccentric exercise to provide faster strength gains after periods of mandatory inactivity such as after surgery or a period of bed rest.

Pavone and Moffat (135) compared isometric torque gains at 60 degrees of knee flexion after healthy females performed either isometric, concentric or eccentric exercise of the quadriceps three times per week for six weeks. The subjects completed three sets of ten repetitions at each training session. The resistance used was determined by calculating three specified percentages (50%, 75% and 100%) of the subject's 10-RM for their respective contraction type. Again, all groups achieved significant gains in isometric torque, but no one training method proved to be superior in promoting these gains.

Komi and Buskirk (105) investigated the effects of seven weeks of eccentric or concentric muscle conditioning on the development of maximal muscle tension. The subjects were divided into three groups. Two of these groups exerted either maximal eccentric or concentric contractions, and a third served as controls. The exercise groups performed six repetitions, four times per week. In contrast to the findings quoted earlier, these authors found that increases in maximal tension development were greater following eccentric conditioning. The eccentric group demonstrated increases over the control group in maximal concentric, eccentric, and isometric tension, whereas the concentric group showed increases in concentric and eccentric, but not isometric tension. On a percentage basis, the eccentric group increased maximal tension more than the concentric group in all three measured forces; however, this difference was significant only for eccentric maximal tension. When changes in maximal isometric tension were compared between the two experimental groups, it was found that the concentric group achieved their final level of maximal tension by the end of the second week of conditioning. The plateau appeared much later for the eccentric group, and this group exhibited a sharp drop in tension during the first week of training that was probably due to muscle soreness.

More recently, several investigators (24, 41, 80, 86) have compared muscular responses following exercise using only concentric contractions to those following a combination of eccentric and concentric training. Some of these investigators also examined the effects of a longer period of training than that used in earlier studies in an effort to look at the time course of strength increases as well as the possible mechanisms involved. Moritani and DeVries (119) have observed that the increase in strength during the early period of weight training is due to neural adaptations, that are not paralleled by increases in muscle fiber size. The following studies attempted to clarify the role of eccentric training in enhancing neural adaptations or inducing muscle hypertrophy.

Colliander and Tesch (24) examined the adaptive response of 22 healthy males to concentric or concentric-eccentric exercise. Subjects either performed five sets of 12 maximal concentric contractions or five sets of six pairs of concentric-eccentric contractions of the quadriceps on a constant velocity dynamometer. Training was done three times per week for 12 weeks. Concentric and eccentric peak torque, vertical jump height and a 3-RM half squat were measured before and after training. Muscle biopsies were taken to determine the effect of training on muscle fiber size. Both groups demonstrated marked increases in overall concentric and eccentric peak torque; however, these increases were significantly greater in the concentric-eccentric group. This group also showed greater improvements in vertical jump height and the 3-RM test. There were no significant differences in muscle fiber area in either group. Therefore, the marked increases in muscle strength were mainly attributed to neural adaptations regardless of the contraction type performed.

Hakkinen and Komi (80) compared the effects of various combinations of eccentric and concentric contractions in competitive and recreational weightlifters. Subjects trained four times per week for 12 weeks. The competitive weightlifters were divided into two groups; one group performed only concentric contractions, and the other performed 75% concentric and 25% eccentric contractions. The recreational athletes were divided into three groups; one group performed only concentric contractions, a second group performed 50% concentric and 50% eccentric contractions, and the third group performed 25% concentric and 75% eccentric contractions. The resistance lifted was equal to 80-100% of the concentric maximum during the concentric exercise, and 100-130% of the concentric maximum during the eccentric exercise. Isometric, eccentric and concentric leg extension force as well as performance in selected lifts were tested prior to, at four week intervals during, and immediately after training. Results showed that the competitive weightlifters who performed only concentric contractions failed to show any improvement in isometric leg extension force after 12 weeks of training, but those who did 25% eccentric exercise improved 8.4%. Similarly, in the recreational weightlifters, those who did only concentric work increased by only 2.4%, whereas those doing 50% eccentric contractions showed a 16% improvement. Those who performed 75% eccentric contractions improved 12.5%. Concentric leg extension force increased considerably in both groups of competitive athletes, but only in the 50% eccentric group of recreational athletes. Interestingly, all groups showed significant increases at the eight week point, but the other two recreational groups experienced a decrease in force on the 12 week test. Eccentric leg extension force failed to improve in either of the competitive groups, but increased significantly in the 75% and the 50% eccentric groups of recreational weightlifters. The authors hypothesized that performance of high tension concentric contractions ensures that the training stimulus reaches the entire motor unit pool while eccentric contractions more efficiently activate the elastic components of the muscle. Therefore, they concluded that combinations of eccentric and concentric exercise are more effective for strength development than concentric exercise alone.

Dudley et al. (41) and Hather et al. (86) both attempted to more thoroughly elucidate the eccentric contribution to strength development and muscle hypertrophy in studies designed after the work of Hakkinen and Komi (80). In both studies, middle-aged males were placed into three exercise groups and a control group. One group performed sets of leg press and leg extension exercises using both concentric and eccentric contractions. The second group performed an equal number of sets of only concentric contractions, and the third group performed twice as many sets as the other two groups and used only concentric muscle actions. The resistance per set was selected to induce failure within six to twelve repetitions. Each group trained two days per week for 19 weeks. All subjects were familiarized with resistance training for one month in an effort to allow expression of the neural adaptation prior to the onset of the studies. The authors felt that the use of this paradigm, combined with the longer training period, would allow examination of the effects of eccentric training on muscle hypertrophy. Subjects in the study by Dudley et al. underwent testing to determine their 3-RM for both exercises prior to and after the training sessions. This testing included an assessment of the concentric, as well as the concentric-eccentric 3-RM. In the study by Hather et al., biopsy samples of the vastus lateralis were obtained before and after training. Results of the muscle biopsies revealed that significantly greater increases in mean fiber area occurred in the group which performed both concentric and eccentric contractions than in either of the other two groups. Increased hypertrophy was seen in both Type I (14%) and Type II (32%) muscle fibers. Strength results demonstrated a predictable hierarchy of improvement in the three groups, with the concentric-eccentric group showing the greatest improvement in all tests. This hierarchy prevailed in testing that involved only concentric muscle actions, although the differences between groups were not as remarkable. The authors concluded that resistance training which includes both concentric and eccentric actions induces greater increases in strength and muscle fiber hypertrophy than does training with concentric contractions alone. Because the resistance imposed by the exercise devices in these studies was essentially equal for the concentric and eccentric actions, the eccentric contractions were submaximal in nature (approximately 50% effort). Therefore, eccentric training may enhance the ability to activate high-threshold, fast-twitch motor units and thereby cause greater increases in strength even when performed at submaximal levels. Furthermore, strength gains are accompanied by increases in mean fiber size.

Specificity of Contraction Mode and Training Velocity in Isokinetic Exercise

Isokinetic exercise is a dynamic form of resistance exercise performed at a predetermined fixed speed against a resistance that is accommodating throughout the range of motion. With the advent of more advanced technology, isokinetic dynamometers now provide resistance in concentric as well as eccentric contraction modes, and both can be performed at a wide range of angular velocities. As a result, many investigators have attempted to determine if muscle strength increases are specific to the training mode and velocity, or if there is physiological overflow between the concentric and eccentric modes and amongst the various velocities.

Mode-Specificity

To date, research involving mode-specific isokinetic training effects has yielded conflicting results. The initial investigation, conducted by Ellenbecker et al. (47) examined the effects of concentric versus eccentric isokinetic training of the rotator cuff muscles. Twenty-two varsity tennis players trained their internal and external shoulder rotators two times per week for six weeks using either eccentric or concentric effort. Six sets of ten repetitions were performed using the velocity spectrum pyramidal ordering concept (60, 180, 210, 210, 180, 60°/sec). Just prior to and immediately after the training period, subjects underwent testing to determine concentric and eccentric peak torque at each of the three training velocities. Significant concentric strength gains were seen in both training groups at all three velocities, indicating an overflow phenomenon of eccentric training to concentric strength gains. Interestingly, the concentric training group showed increased eccentric strength at most speeds, while the eccentric group exhibited no improvements in eccentric strength.

Duncan et al. (42) studied mode-specificity during isokinetic training of the quadriceps in 48 untrained males aged 18 to 32 years. Subjects were separated into three groups, those who trained eccentrically, those who trained concentrically, and a control group that did no training. Average force at three different velocities was assessed before and after a six-week training period. Subjects trained three times per week. At each training session, they performed four submaximal and one maximal warm-up repetitions followed by ten maximal repetitions at 120°/sec using the assigned contraction type. The eccentric training group had significant gains in eccentric force at all three speeds, but demonstrated no improvement in concentric force at any speed. The concentric group showed modest increases in both concentric and eccentric force at all speeds, but these increases were only significant at the highest concentric speed. The authors concluded that the eccentric isokinetic mode has highly specific strength training effects, while the concentric mode has less specific training effects.

Tomberlin et al. (171) obtained similar results in their study comparing the effects of isokinetic eccentric and concentric quadriceps training. Sixty-three untrained volunteers were divided into the same three groups described in the previous study. The two training groups performed three sets of ten maximal concentric or eccentric repetitions at a velocity of 100°/sec. Subjects trained three times per week for six weeks. After training, the eccentric training group showed significant gains in eccentric peak torque and total work, but demonstrated no improvement in concentric performance, thus supporting the concept of mode-specificity in eccentric training. On the other hand, although the concentric group achieved greater gains in the concentric parameters, they also demonstrated significant increases in eccentric peak torque and total work.

The mode-specificity of eccentric isokinetic quadriceps training was further confirmed by Storm et al. (161). They evaluated changes in work production after 14 females underwent six weeks of either eccentric or concentric training at 120°/sec. Work performance of the quadriceps muscle was measured at three velocities before and after training. Subjects in the eccentric training group showed significant gains in eccentric but not concentric work production. Again, the concentric training group demonstrated significant improvement in both eccentric and concentric work production.

Ryan et al. (141) examined the mode-specific effects of isokinetic eccentric training of the hamstring muscles. Thirty-four female college students were assigned to an exercise group and a non-exercise group. Prior to training, all subjects were tested concentrically and eccentrically at three increasing velocities (60, 120 and 180°/sec). Subjects in the exercise group trained eccentrically at 120°/sec. Fifteen maximal repetitions were performed three times per week for six weeks. After training, test results showed that the exercise group increased significantly in eccentric force at all tested speeds and increased concentrically at the two higher velocities. Thus, it was concluded that eccentric isokinetic training of the hamstrings is not mode-specific.

Bishop et al. (9) investigated the effect of eccentric isokinetic training on the concentric strength of the quadriceps and the hamstrings. Forty-three untrained males underwent concentric pretesting at 60 and 180°/sec. Twenty-eight subjects were then eccentrically trained three times per week for eight weeks. The remaining subjects comprised the control group and did not train. The quadriceps muscle did not show any significant improvement in concentric strength after eccentric training, however, the hamstrings did exhibit a significant increase in concentric torque. These findings appear to concur with the results of the previous investigations regarding mode-specificity as it relates to these two muscle groups. The authors hypothesized that the disparity in results between muscle groups may be due to differences in fiber-type composition, differences in functional use of the muscle groups, and differences between two-joint (hamstrings) and one-joint (quadriceps) muscles.

Specificity of Velocity

The concept of physiologic overflow through at least a portion of the velocity spectrum has been well documented during concentric isokinetic exercise. However, there is disagreement about the nature and magnitude of the overflow phenomenon. The earliest investigations by Moffroid and Whipple (116) showed that exercise at a specific training velocity (108°/sec) resulted in improvements at speeds slower than that velocity, although training at a lower velocity (36°/sec) had no carryover to higher velocities. Lesmes et al. (109) obtained similar results in their study. In contrast, Calozzo et al. (13) found that slow velocity training at 60°/sec achieved strength gains at all tested velocities except 300°/sec. They also showed that training at 240°/sec resulted in strength increases at 180, 240 and 300°/sec, but not at slower velocities.

Kanehisa and Miyashita (100) studied the overflow effects of slow, intermediate and fast training speeds on power outputs at various velocities. They found that high velocity training enhanced power only at higher test speeds. Slow velocity training resulted in increased power at all test speeds, but these improvements were diminished with increasing test velocity. Intermediate velocity training produced significant gains at all test speeds which were similar in magnitude. The authors recommended use of this intermediate training speed to enhance muscle power over a wide range of contraction velocities.

Timm (168) further investigated the overflow phenomenon by training the quadriceps and hamstrings of 30 subjects at a speed of 180°/sec. Subjects were tested at the velocity spectrum speeds of 60, 120, 180, 240, and 300°/sec before and after the training period. Results revealed significant differences in quadriceps and hamstring peak torque and average power at all velocity spectrum speeds. The author concluded that the effects of exercise exhibit a 120°/sec physiological overflow to both slower and faster velocities following concentric isokinetic training.

The velocity-specific effects of eccentric isokinetic exercise have not been as widely investigated as have their concentric counterparts. However, there does appear to be a greater consensus of opinion regarding these effects. Eccentric isokinetic training has been shown to demonstrate at least a 120°/sec carryover to other test speeds. The classic study by Duncan (42) which was outlined earlier, demonstrated that eccentric training of the quadriceps at 120°/sec produced significant improvements in force output at both 60 and 180°/sec. Storm et al. (161) replicated these results and also reported significant carryover to a higher velocity of 210°/sec. A similarly designed investigation by Ryan et al. (141), produced comparable results in the hamstring muscles. Yanagi et al. (182) reported physiologic overflow from a training speed of 180°/sec to a test speed of 60°/sec after subjects performed three sets of 15 maximal repetitions of the thigh muscles three times per week for six weeks. However, they did not specify the muscle group from which the data were gathered. In the previously described study by Bishop et al. (9) which examined mode-specificity, it was also determined that eccentric training velocity had no influence on the magnitude of concentric strength gains at any tested velocity.

Concentric Vs. Combined Concentric-Eccentric Isokinetic Exercise

Several authors (9, 159, 171) have advocated the use of eccentric exercise during the training and rehabilitation of athletes; but the specific effects of adding eccentric isokinetic exercise to a traditional concentric isokinetic training program have just recently been noted. Lacerte et al. (108) examined the effects of concentric-only versus combined concentric-eccentric isokinetic training at two training velocities. Twenty-five male subjects, aged 25 to 35, were assigned to one of five training groups. Two groups performed concentric-only contractions; one group at 60°/sec, and the other at 180°/sec. The other two groups performed both concentric and eccentric contractions at one of the same two speeds. The final group of subjects served as controls. Subjects in the concentric-only groups completed 20 maximal concentric contractions of the quadriceps at each training session, while the mixed groups did ten concentric and ten eccentric repetitions. All subjects trained for 12 weeks. Concentric and eccentric peak torque was measured at four test velocities (60, 120, 180 and 240°/sec) prior to and following the training interval. All trained subjects made significant gains in peak torque; however, these gains were significantly greater in the mixed contraction groups. Again, training velocity had no effect on average peak torque gains, and the observed improvements were not specific to the training velocity. These findings indicate that the addition of an eccentric component to a concentric isokinetic program will enhance improvements in peak torque regardless of the training speed.

CHAPTER III

MATERIALS AND METHODS

Part I

Subjects

Thirty healthy, untrained subjects (3 males, 27 females) between the ages of 18 and 40 volunteered to participate in the study. A maximum age limit was imposed because specific skeletal muscle changes with advancing age include selected atrophy of type II fibers which appear to be preferentially recruited during eccentric contractions (61, 138). Volunteers were recruited from employees of the Fort Sanders Regional Medical Center physical therapy department, students and faculty members of Pellissippi State Technical Community College, and students of the University of Tennessee. Prospective subjects were screened for age, orthopedic history of the lower extremities, and training history. Prior to participation, a health status questionnaire was completed by each individual (Appendix D), and informed consent was obtained in accordance with guidelines established by the University of Tennessee Committee on Research Participation (Appendix E) Subjects were randomly assigned to one of three exercise groups, namely (a) 100% maximum effort, (b) 80% maximum effort, or (c) 60% maximum effort. Each group consisted of nine females and one male. Subjects were instructed to refrain from beginning any training or novel exercise during the period of the study other than that specified in the experimental protocol. They were also requested not to take any analgesic or anti-inflammatory medication during the testing period.

Criteria for exclusion of subjects:

(1) Age <18 or >40 years,

(2) A history of knee surgery or serious pathology of the knee, quadriceps or hamstrings,

(3) Involvement in lower extremity strength training within 8 weeks prior to entering the study,

(4) Inability to maintain torque output at the assigned submaximal intensity level during the initial practice session, or

(5) Maximal eccentric torque production greater than the maximum capacity of the dynamometer (300 foot pounds).

Experimental Protocol

The experimental procedure consisted of five sessions. All sessions for each subject were held over a two week time period at Fort Sanders Center For Sports Medicine, Knoxville, Tennessee. Sessions two through five occurred one week after the initial session to allow complete recovery from the initial exercise bout. These sessions were conducted on four consecutive days at the same time each day. A summary of the sequence of events which occurred at each session is outlined in Appendix C-1.

All strength testing and the eccentric exercise bout was accomplished using a Biodex isokinetic dynamometer (Biodex Corporation, Shirley, NY). Biodex Advantage software Version 3.2 was used for data collection and reduction. The dynamometer was calibrated according to the manufacturer's specifications (8) at the start of each testing day. The mechanical and physiological reliability of the Biodex has been shown to be high when testing eccentric torque output of the quadriceps and hamstrings. (ICC for mechanical reliability = 1.00; ICC for physiological reliability = 0.98) (169, 170). Testing was limited to the right lower extremity.

Eccentric Isokinetic Practice Session

Prior to the practice session, each subject completed a five minute submaximal warm-up on a Tunturi Protrainer cycle ergometer using a low resistance setting (2) and a pedal rpm of 90. It was followed by a 30 second static stretch of the quadriceps and the hamstrings of both legs. In order to familiarize themselves with the Biodex, subjects then practiced performing eccentric contractions with their left quadriceps and hamstring muscles. The left leg was used because performance of one bout of eccentric exercise on the right leg (which was involved in all subsequent testing) could produce an adaptation such that the muscles would be more resistant to damage from a second exercise bout, and therefore, the responses would be reduced (19, 20, 21, 44, 75, 121, 132).

Subjects in the 100% group practiced five maximal eccentric contractions with each muscle group. Subjects in the 60% and 80% group performed two maximal contractions and then practiced submaximal contractions until they demonstrated consistency in maintaining torque output at the assigned level. The instrumentation used to accomplish this task is described in a later section. If the subjects could not achieve proficiency in maintaining their submaximal torque level after 15 repetitions, they were eliminated from the study because it was unlikely that they would maintain the appropriate level during the exercise bout.

Maximal Eccentric Isokinetic Test

Each subject was tested for maximal eccentric isokinetic peak torque at 60^{o}/sec. Subjects were in a seated position with the hips flexed at 80 degrees. The axis of the dynamometer was visually aligned with the transverse axis at the knee. The inferior aspect of the lever arm pad was positioned 2 cm above the medial malleolus of the tibia. Stabilization was achieved by placing the standard Velcro straps around the waist, over the distal thigh, at the shin and crossed over the chest. Subjects were instructed to cross their arms over their chest and hold onto the straps. A hard deceleration cushion and medium (C) sensitivity setting were used as recommended by the manufacturer (8). Range of motion limits were set at 0 degrees and 110 degrees. The passive setting was used to achieve a modified eccentric mode (172). Gravity corrections were calculated automatically by the Biodex software (52, 175).

Subjects were asked to perform maximal reciprocal contractions of the hamstrings and quadriceps by pushing back on the lever arm as it moved their limb from flexion into full extension, and pulling up on the lever arm as it returned their limb to the flexed position. A two second pause occurred at each end range of motion to allow the subject to prepare for the next contraction. Testing was preceded by two submaximal warm-up repetitions and one maximal repetition. Five maximal repetitions were then recorded. Standardized verbal encouragement was given throughout the test.

Eccentric Isokinetic Exercise Bout

Each subject performed an isokinetic eccentric exercise bout at the pre-selected percentage of their maximal effort as determined by the maximal eccentric test. Subjects exercised in the same position described for the test. Contractions were performed using the passive setting of the Biodex dynamometer to achieve a modified eccentric mode. The angular velocity was set at 60^{o}/sec.

Subjects completed three sets of 15 eccentric contractions with each muscle group, as this is the optimal number of repetitions needed to achieve eccentric isokinetic power gains (87, 182). Each set was separated by a two minute rest period. Continuous torque recordings from the dynamometer and a target line which indicated the desired torque output value were displayed on a computer screen. The subjects were asked to maintain their torque output as close to the target line as possible. The torque generated during each repetition was recorded and checked to ensure that the required values were produced. Subjects performed the contractions with each muscle group individually, and after each eccentric contraction was completed, the leg was passively returned to its starting position. The order in which the two muscle groups were exercised was chosen randomly.

Indicators of Muscle Damage

Several indicators of muscle damage were measured immediately prior to the exercise bout and at 24, 48 and 72 hours thereafter. These indicators were muscle soreness rating, muscle soreness perception, range of motion, maximal isometric torque production, and serum creatine kinase activity.

Muscle Soreness Rating

Subjects were asked to rate their muscle soreness using a graphic pain rating scale developed by Denegar (34). (Appendix C-2) This scale was based on the verbal descriptive scale designed by Talag (163) to assess delayed onset muscle soreness. Graphic rating scales are similar to visual analog scales, but have descriptors spread across the scale in addition to those at the extremes. Verbal descriptive scales have been criticized for being insensitive to small changes, whereas visual analog scales are a sensitive and reproducible means of expressing pain severity (93). They have been proven to be reliable and valid as a ratio-scaled measure of pain (139). However, use of graphic pain rating scales has resulted in a more uniform distribution of scores, with no tendency for scores to cluster together when compared with both visual analog scales or verbal descriptive scales (149).

Pain was quantified by measuring the distance to the nearest 1/10 cm from the extreme left of the graphic pain rating scale to the mark made by the subject at the point on the 12 cm line they felt best described their muscle soreness. The subject marked one pain rating scale for each muscle group tested.

Muscle Soreness Perception

Muscle soreness perception was evaluated each day using a method similar to that described by Edwards et al. (45), Newham et al. (125), and Hasson et al. (84, 85). The subject was first asked to assume a prone position, and a heavy polyurethane sheet marked with a grid of intercepts 2 cm apart (used as soreness test sites) was attached to the posterior surface of the thigh, covering the entire hamstring musculature. The skin was marked to ensure consistent positioning on subsequent test days. A round-ended wooded probe (2 cm in diameter) was attached to a calibrated spring mechanism. (Pain Threshold Gauge; North Coast Medical, Inc., San Jose, CA) At each test site, a gradually increasing force was applied up to a maximum of 58 Newtons. The subject was asked to verbally indicate when the sensation of pressure changed to one of discomfort at which time the probe was immediately withdrawn. The amount of force was then recorded. If no indication of discomfort was reported up to 58 N, soreness was considered to be absent at the 2 cm site. Each site was tested in a standard order to ensure a complete evaluation of the entire hamstring muscle group. The subject was then asked to assume a seated position with the knee bent at 90 degrees. A second polyurethane grid was attached to the anterior surface of the thigh covering the entire quadriceps musculature, and the entire procedure was repeated.

The intensity of the muscle soreness was defined as the inverse of the amount of force applied to each 2 cm site to evoke a change in the subject's perception of pressure to that of soreness. The mean intensity for each subject was the summed measured values divided by the number of individual 2 cm areas testing positive for muscle soreness. The test-retest correlation for this measurement is high (r=0.91) (85). The area of muscle soreness was defined as the estimation of the amount of the quadriceps or hamstrings muscles that had muscle soreness. This value was obtained by testing at each 2 cm site and dividing the number of sites testing positive for soreness by the total number of test sites. The muscle soreness perception for each subject was the product of intensity and area and was determined separately for each muscle group.

Range of Motion

Hamstring range of motion was assessed using the active knee extension test as described by Gajdosik(65) and Worrell (180). Each subject was placed in a supine position with the right hip positioned at 90 degrees of flexion. The subject then stabilized the hip in this position by placing both hands around the distal thigh, just proximal to the knee joint with the fingers interlocked. The right foot was placed in a relaxed, plantar flexed position because ankle dorsiflexion may limit knee extension due to tightness of the gastrocnemius muscle (66). The opposite leg was maintained in 0 degrees of hip flexion. A universal goniometer was used to set the position of both hips. The stationary arm was parallel to the long axis of the trunk, and the movable arm was placed parallel to the lateral midline of the femur. The axis of the goniometer was aligned over the greater trochanter of the femur. To determine hamstring flexibility, the knee was actively extended while the subject maintained the hip at 90 degrees of flexion. The stationary arm of the goniometer was placed parallel to the midline of the femur, and the movable arm was placed parallel to the midline to the fibula. The range of motion measurement was taken at the point where extreme resistance to extension was encountered. It was defined as the number of degrees from complete (0^{o}) knee extension. Two measurements were taken, and the average was recorded. The test-retest reliability of the active knee extension test is high (ICC=0.86) when performed in this manner (66).

Active knee flexion range of motion was measured to assess flexibility of the quadriceps. Each subject was placed in a supine position with both hips and knees fully extended. The right knee was then actively flexed as far as possible, and the knee flexion angle was measured goniometrically. Goniometer placement was identical to that used to determine range of motion in the passive knee extension test. Two measurements were taken and the average was recorded.

Maximal Voluntary Isometric Contraction

Maximal voluntary isometric knee extension and flexion contraction was measured on the Biodex dynamometer with the knee stabilized at 60 degrees of flexion. Two other angles (90^{o} and 30^{o}) were also tested, but these were not included in the analysis. In a pilot study, the isometric mode of the Biodex demonstrated a high level of reliability for knee extension (ICC = 0.92) and knee flexion (ICC = 0.99). The subjects were seated and stabilized in the same manner described for the maximal eccentric test. Range of motion was calibrated as prompted by the computer software, and the 60 degree contraction angle was verified. Each subject performed three submaximal and one maximal warm-up repetitions followed by three maximal test contractions. Each contraction was held for five seconds with a five second rest period between repetitions. Standardized verbal encouragement was given by the investigator during each contraction. The quadriceps were tested first, followed by the hamstrings. Data were collected using Biodex computer software, and the maximum average torque was recorded.

Monitoring of Serum Creatine Kinase Activity

Sampling Technique

Blood samples were drawn by venipuncture from the antecubital region just before and at 24, 48, and 72 hours following the eccentric exercise bout. Blood was collected in a 5 ml sterile vacutainer containing 0.07 ml of 15% EDTA fitted with a 21 gauge needle (Becton Dickson, Rutherford, New Jersey, USA). After collection, the blood was centrifuged for 10 minutes at 5000 rpm. After centrifugation, the samples were examined visually for possible hemolysis. The serum was drawn off with a 3.0 ml syringe and placed in a polystyrene storage tube, capped and labeled. Samples were stored in a freezer at -20^{o} C, until the time of creatine kinase analysis.

Creatine Kinase Assay

Creatine kinase activity was analyzed using a Sigma Diagnostics test kit Procedure No. 47-UV (Sigma, St. Louis Missouri, USA) at a temperature of 30^{o}C. The assay procedure is described in Appendix C-3.

Statistical Analysis

Descriptive statistics (means and standard deviations) were computed on all descriptive variables (height, weight, and age) obtained in Part I of the study.

A three-way ANOVA (group x gender x time) with repeated measures was first used to test each of the hypotheses 1-6 concerning differences in the various indicators of muscle damage. However, gender was not found to be significant, and thus, was dropped from the analysis. The hypotheses were each then tested using a two-way ANOVA (group x time) with repeated measures. When significant group effects were found, least significant difference (LSD) post-hoc tests were used to determine the nature of the differences between groups.

When testing hypothesis 7, creatine kinase measurements were converted to logarithmic values due to their exponential pattern of elevation. A three-way ANOVA (group x gender x time) with repeated measures was used to analyze the creatine kinase response. The differences between means were also examined using LSD post-hoc tests to ascertain the nature of the differences in CK response at each tested time interval.

A three-way ANOVA (group x muscle x time) with repeated measures was used to determine the differences in degree of perceived muscle soreness exhibited by the hamstrings and quadriceps muscles (hypotheses 8-10). If significant differences occurred, the adjusted (least-squares) means were compared to determine specific group x muscle differences at each tested time interval.

Statistical procedures were performed using the GLM procedure in the Statistical Analysis System (SAS) (143). Differences were deemed to be significant at $p < .05$.

Part II

Subjects

Forty subjects (7 males, 33 females) of equivalent age range, health and training status to the subjects in Part I, volunteered to serve as subjects for this part of the study. Recruitment, screening and exclusion of volunteers occurred in the same manner as described previously. Subjects were randomly assigned to one of three training groups, namely (a) 100% maximum effort, n=10; (b) 80% maximum effort, n=10; (c) 60% maximum effort, n=10; or to the control group, n=10. The control group completed the pretest and the posttest, but did no training. All participants were instructed to maintain their normal activity level and to refrain from beginning any lower extremity weight training other than that specified in the experimental protocol.

Experimental Protocol

This part of the study was carried out at the Fort Sanders Center for Sports Medicine central clinic as well as at the center's west clinic. Both clinics are equipped with a Biodex isokinetic dynamometer, and both were used for the isokinetic testing and training sessions in order to accommodate subject preference. Intermachine reliability of the Biodex dynamometer is high (ICC = 0.95 for knee extension and 0.92 for knee flexion); therefore, data from one Biodex can be compared to that from another (178). The eccentric reliability of the dynamometer was stated in Part I. The concentric reliability is also high when testing knee flexion and extension at all speeds (11, 50, 78, 102, 115, 117, 166, 170). Both dynamometers were calibrated according to the manufacturer's specifications at the start of each testing and training day (8). Biodex Advantage software Version 3.2 was used for data collection and reduction. All data were windowed to eliminate end-point isometric spike artifacts (78, 177). The experimental procedure consisted of a pretest, eight weeks of eccentric isokinetic training, and a posttest. All testing and training was again limited to the quadriceps femoris and hamstring muscles of the right lower extremity. A summary of the sequence of events which occurred during the pretest and posttest sessions is outlined in Appendix C-4. In addition, the graphic pain rating scale described in Part I was completed by each subject at the beginning of all testing and training sessions in order to monitor muscular adaptation to the eccentric training.

Pretest

Two days prior to the onset of training, subjects underwent a pretest which included a single leg hop for distance, a concentric isokinetic velocity spectrum test, and an eccentric isokinetic velocity spectrum test.

Single Leg Hop for Distance

The single leg hop for distance was administered in order to determine whether or not the various training intensities would elicit improvement in a functional test. It has been recommended by several authors as a valuable lower extremity functional assessment which can be performed in a clinical setting (7, 28, 110, 133).

A 2.5 meter strip of white athletic tape was placed on the clinic floor and marked off in centimeters. Subjects stood on their right leg with their toes touching the zero mark, and their arms by their sides. They were instructed to hop forward as far as possible and land on the same leg. The distance from the zero line to the heels was measured and recorded. Each subject performed three hops, and the average distance was calculated. When performed in the manner described, the single leg hop for distance is highly reliable and contains small measurement error (ICC = 0.99; SEM = 3.50 cm) (10).

Concentric Isokinetic Velocity Spectrum Test

Concentric peak torque and average power were tested at the angular velocities of 60, 180, 300 and 450°/sec, in ascending order. Subjects were positioned and stabilized as described in Part I. All position settings were recorded to facilitate accurate posttest duplication. Gravity correction was calculated by the computer software. Subjects were instructed to kick out and pull back against the dynamometer's lever arm as hard and fast as possible. Testing was preceded by four submaximal and two maximal warm-up contractions at each velocity. Five maximal contractions were then recorded. Testing at each velocity was followed by a one minute rest period. Standardized verbal encouragement was given by the investigator throughout each test.

Eccentric Isokinetic Velocity Spectrum Test

After a 15 minute rest period, eccentric peak torque and average power were measured at the angular velocities of 30, 60, 90 and 120°/sec. The eccentric test procedure is described in Part I. Testing began with the slowest velocity and proceeded in ascending order. There was a two minute rest period between tests at each velocity.

Eccentric Isokinetic Training

Subjects in the three exercise groups trained three times per week (Monday, Wednesday, Friday or Tuesday, Thursday, Saturday) for eight weeks. The training sessions were identical to the eccentric exercise bout described in Part I. The order in which the two muscle groups were exercised was alternated at each session.

After four weeks of training, a retest was administered at the training velocity (60^{o}/sec), and the target torque levels for each subject were reset to equal the appropriate percentage of their new peak torque values. This procedure was repeated at the six week point.

Posttest

At end of the eight week training period, a posttest identical to the pretest was performed. The posttest data was collected two days after the last training session.

Statistical Analysis

Descriptive statistics (means and standard deviations) were computed for the descriptive variables(height, weight, and age) obtained in Part II of the study. The eight hypotheses concerning changes in strength and power of the quadriceps and hamstrings were each tested using a two-way analysis of covariance (group x time) with repeated measures. Initial eccentric peak torque at the training speed (60^{o}/sec) was used as a covariate in each analysis. When a significant group effect was found, the adjusted (least-squares) means were compared to determine the nature of the differences between groups.

A two-way analysis of covariance (group x time) with repeated measures was also used to test hypothesis 9 concerning changes in the functional single leg hop for distance test. Two covariates (initial eccentric peak torque of the quadriceps and initial eccentric peak torque of the hamstrings at the training speed) were included in this analysis. Adjusted means were compared to locate specific group differences.

Statistical procedures were performed using the GLM procedure in the Statistical Analysis System (SAS) (143). Differences were deemed to be significant at $p < .05$.

CHAPTER IV

RESULTS

The descriptive and physical characteristics of the thirty subjects in part I and the forty subjects in part II are presented in Tables 1 and 2. (Appendix A) All subjects in both parts of the study were randomly assigned to their respective exercise groups.

Part I

Indicators of Muscle Damage

All indicators of muscle damage were measured immediately prior to the exercise bout and at 24, 48 and 72 hours thereafter. Comparisons were made for each of the four measurement times. Statistical comparisons using means and standard errors are presented in Appendix A.

Muscle Soreness Rating

The group means for muscle soreness ratings of the quadriceps and hamstrings are presented in Figures 1 and 2. A significant time effect ($p < .0001$) and a significant time x group interaction (quadriceps: $p < .0001$; hamstrings $p < .0007$) were found, indicating that the eccentric exercise bout did induce muscle soreness in both muscle groups and that the soreness response differed between exercise groups. No significant soreness was present in any

All Figures and Tables are found in Appendix B group prior to the exercise session, and the 60% group failed to exhibit any significant soreness at any time after the exercise bout. However, at 24 hours post-exercise, the 100% group had developed significantly more soreness than either the 60% or 80% group. The soreness response reached its peak at 48 hours in the 100% and 80% groups. The 100% group remained significantly more sore than the 80% group which in turn, reported more soreness than did those exercising at 60% effort. By 72 hours post-exercise, soreness in both submaximal groups had returned to baseline levels, but the 100% group continued to report significant discomfort. There were no significant differences in the soreness ratings of the quadriceps as compared to the hamstrings in any exercise group.

Muscle Soreness Perception

The results of the muscle soreness perception tests are shown in Figures 3 and 4. Muscle soreness perception increased significantly after the exercise bout (quadriceps: $p < .0007$; hamstrings: $p < .0001$) in both muscle groups. Slight soreness was present in some subjects prior to the exercise bout (residual soreness from the initial pretest), but this soreness was not significant. Although soreness perception at 24 hours was significantly higher than that reported prior to the exercise session (quadriceps: $p < .0007$; hamstrings: $p < .0016$), there were no significant differences in soreness between exercise groups in the hamstrings, and soreness perception in the quadriceps only differed between the 60% and 100% groups. At 48 hours the soreness perception of the 100% group was significantly greater in both muscle groups than that reported by either of the submaximal exercise groups. At 72 hours post-exercise, the 100% group still reported significantly more soreness in both muscle groups than did the 60% group; however, no differences were seen between either the 80% and 100% groups or the 60% and 80% groups.

Muscle soreness perception only differed between muscle groups in the 100% group at 24 hours. Soreness perception of the quadriceps was significantly greater than that of the hamstrings at this time ($p < .0291$). No other differences in the soreness perception of the two muscle groups were found.

Location of Soreness

The mean amount of pressure required to provoke muscular discomfort during each test session was determined by group for each 2 cm test site (Figures 10-a - 10-l, and Figures 11-a - 11-l). In the quadriceps femoris, soreness appeared first and became the most pronounced in the proximal-lateral and the distal-medial regions of the muscle group. This pattern was consistent across groups; although soreness increased and became more diffuse as exercise intensity increased. A large portion of the muscle was spared in the 60% group, but in the 100% group, most test sites exhibited soreness in at least some subjects. Relatively speaking, less soreness was demonstrated by the rectus femoris than by the other muscles in the quadriceps group. However, mean soreness values often failed to reach significance at a specific test site due to the amount of variation between subjects.

Although a great deal of intersubject variation was also present in the hamstring muscles, soreness was more pronounced in the distal portion of the muscle belly and at the tendinous insertions. Again, the affected areas became more widespread as the intensity of exercise escalated.

Range of Motion

Changes in range of motion are presented in Figures 5 and 6. No significant decreases in knee flexion range of motion occurred in any group, indicating that there was no measurable change in quadriceps flexibility. The repeated measures analysis of the exercise effects on hamstring flexibility revealed a significant overall decrease in hamstring range of motion over time ($p < .0036$) which differed according to exercise group (time x group interaction = $p < .0295$). In subjects exercising at 100% effort, hamstring range of motion decreased significantly (7 degrees) by the 24 hour point and declined an additional 4 degrees at 48 hours. Range of motion in this group remained significantly lower than baseline levels at 72 hours post-exercise. Hamstring flexibility was not significantly altered in either of the submaximal exercise groups.

Maximal Voluntary Isometric Strength

Group means for maximal isometric strength of the quadriceps and hamstrings are shown in Figures 7 and 8. A significant time effect ($p < .0153$) and a significant time x group interaction ($p < .0428$) were found for the quadriceps in the repeated measures analysis. Contrast testing revealed mean quadriceps strength to be significantly lower than pretest values at 24 hours ($p < .0104$) and 48 hours ($p < .0248$) post-exercise. The 100% group exhibited the greatest decrease in maximal isometric strength (18%). A 10% decline was seen in the 80% group. However, these values did not reach significance when the three groups were compared at each time period.

A significant time effect ($p < .0082$) also occurred in the analysis of maximal isometric hamstring strength. Overall, measurements of mean hamstring strength were significantly lower than baseline at both the 24 hour ($p < .0025$) and the 48 hour ($p < .0486$) measurement sessions. Maximal hamstring strength dropped by 26% in the 100% group, and very little recovery was noted 72 hours after the exercise bout. A smaller decrease in strength (13%) was noted in the 80% group one day post-exercise, but baseline values were regained 24 hours later. Strength values remained constant in the 60% group. However, post-hoc comparisons of the three groups failed to detect a significant difference in strength between groups at any one time period.

<u>Serum Creatine Kinase Activity</u>

The results for blood CK activity are presented in Figure 9. Although there was a large intersubject variability in the CK response, the log CK analysis revealed a significant time effect ($p < .0003$) as well as a significant time x group interaction ($p < .0002$) indicating that the degree of creatine kinase elevation differed between the three exercise intensities. Gender also played a role in the nature of the CK response with males exhibiting significantly higher CK levels over time ($p < .0024$).

Prior to the exercise bout, the mean CK levels were 103, 226 and 306 IU/L for the 60%, 80% and 100% groups respectively. The values for both the 80% and 100% groups were higher than the expected normal CK values for a clinically healthy population, which could indicate that subjects experienced increased CK levels as a result of the practice session and pretest performed the previous week. The maximal exercise group exhibited significantly higher

CK levels immediately prior to the eccentric exercise bout than either the 60% ($p < .0065$) or the 80% group ($p < .0196$). The two submaximal groups were not, however, significantly different from one another.

At 24 hours post exercise, the CK level of the 100% group climbed to 494 IU/L. A very slight CK increase (11 IU/L) was noted in the 60% group while the CK values in the 80% group actually decreased by 46 IU/L. The log CK value of the maximal exercise group was significantly higher than that of either submaximal group ($p < .0163$; $p < .0306$).

At 48 and 72 hours post exercise, CK levels in the 100% group continued to rise sharply to 1572 and 3932 IU/L at each respective time period. In contrast, CK values decreased in the two submaximal groups at both time periods and were actually lower than pre-exercise levels by 72 hours after the exercise bout. Again, there were significant differences between the maximal exercise group and the two submaximal groups at both time periods ($p < .0223$ at 48 hours, $p < .0001$ at 72 hours). No significant differences in the CK activity of the 60 and 80% groups were seen at either 48 or 72 hours.

Part II

Strength and Power Changes

Eccentric and concentric peak torque, average power and performance on a functional single leg hop for distance test were assessed before and after an eight week period of eccentric isokinetic training. Isokinetic performance was evaluated at four different velocities. Group comparisons were made for all post-test scores. Comparisons using means which are adjusted for the covariates are presented in Appendix A.

Eccentric Peak Torque

Only 39 subjects were included in the analysis of eccentric quadriceps peak torque because one subject exceeded the 300 foot pound eccentric torque capacity of the dynamometer after two weeks of training. Eccentric peak torque of the quadriceps increased significantly at the training velocity (60°/sec) in all three exercise groups as compared to the control group (Figure 13). The 80% group exhibited the greatest gains, and both the 60% group ($p < .0448$) and the 80% group ($p < .02$) improved significantly more than the 100% group.

Significant improvements in eccentric quadriceps peak torque also occurred at the other three test velocities (Figures 12, 14, 15). At 30°/sec, significant increases were seen in all training groups, and again, the 80% group made significantly more improvement than did the 100% group ($p < .0434$). At 90°/sec, significant improvements occurred in the 60% ($p < .0008$) and 80% ($p < .0015$) groups. No improvements were noted in either the 100% group or the control group. At 120°/sec, all three treatment groups again demonstrated significant peak torque gains as compared to the control group. Improvements in both the 60% group ($p < .0140$) and the 80% group ($p < .0065$) were greater than those seen in the group that exerted 100% effort.

The eccentric peak torque of the hamstrings at the training velocity also improved significantly in all three exercise groups, with no improvement noted in the control group (Figure 17). The 80% group demonstrated the greatest torque gain, but this increase was not significantly different from that exhibited by the other two exercise groups.

Significant improvements also occurred in all exercise groups as compared to the control group at the slower speed of 30°/sec (Figure 16). Again, no significant differences were found between the three training groups. Results of testing at 90 and 120°/sec revealed that no significant eccentric peak torque gains were found in either the control group or the 60% group while the 80% and 100% groups demonstrated equally significant improvements in eccentric peak torque (Figures 18 -19).

Concentric Peak Torque

No significant increases in concentric peak torque were found at any of the tested velocities in the quadriceps following eccentric isokinetic training (Figures 20 -23). In the hamstrings, there was significant improvement by the 80% group at the training velocity of 60°/sec, but no other significant gains occurred (Figures 24 - 27).

Average Power

Average power did not change significantly at any velocity following eccentric training of the quadriceps, regardless of training group (Figures 28 - 31). In the hamstrings, average power at 60°/sec increased significantly in all three training groups as compared to the control group (Figure 32). The magnitude of the improvement did not differ between training groups. When tested at 180°/sec, only the 80% group demonstrated an increase in average power ($p < .0077$) when compared to the control group (Figure 33). At

300^{o}/sec, average power increased in both the 80% ($p < .0028$) and the 100% ($p < .0120$) groups, but not in the 60% group (Figure 34). No significant changes in average power were seen at the highest test velocity (450^{o}/sec) in any of the four groups (Figure 35).

Single Leg Hop for Distance

Eccentric isokinetic training of the quadriceps and the hamstrings did not result in significant improvements in the functional single leg hop for distance test in any of the training groups (Figure 36).

CHAPTER V

DISCUSSION

The purpose of this investigation was to examine the effects of submaximal eccentric isokinetic exercise on indicators of muscle damage, and to determine if strength and power gains can be produced by submaximal eccentric isokinetic training. In part I of the study, the effects of a single bout of eccentric isokinetic exercise on soreness perception, range of motion, strength and creatine kinase blood levels were examined. These effects were then compared between the two muscle groups tested. In part II, the effects of an eight week submaximal eccentric isokinetic training program were investigated. The nature of any training-induced strength and power gains in terms of specificity of contraction mode and velocity were determined.

Part I

Indicators of Muscle Damage

Muscle Soreness Rating

Results of the muscle soreness ratings via the graphic pain rating scale revealed that performance of three sets of fifteen maximal eccentric isokinetic contractions at a velocity of 60^{o}/sec does cause significant muscle soreness in both the quadriceps and the hamstring muscles. By 24 hours after the exercise bout, subjects reported a pain rating of 3.59 cm in the quadriceps and 3.99 cm in the hamstrings, which falls between "discomfort during activity" and "awareness of pain without distress" according to the scale's verbal descriptors. (Appendix C-2) Peak discomfort in both muscle groups occurred 48 hours post-exercise, and was at a level which began to distract the subject's attention during physical activity (4.61 cm in the quadriceps; 4.72 cm in the hamstrings). These values are slightly higher than the 3.97 cm rating on the visual analog scale reported by Kulig et al. (107) two days after subjects performed eccentric isokinetic exercise of the hamstrings until they failed to reach 90 percent of peak torque (an average of 44.8 maximal repetitions). Values in the present study are also higher than the peak soreness rating of 1.40 cm on a visual analog scale reported by Fitzgerald et al. (53) after subjects performed seven sets of ten maximal eccentric isokinetic contractions of the quadriceps at a velocity of 30^{o}/sec. Although some subjects in that study did report pain measuring up to 4.7 cm, the mean scores were much lower due to large intersubject variation. The higher values in the current study could be due to the faster exercise velocity. Previous authors have reported an increase in muscle soreness as the velocity of isokinetic exercise increases (148). An alternative explanation could be the use of a slightly different measurement instrument (graphic pain rating scale vs. visual analog scale).

Neither of the submaximal groups in this study reported pain that was any greater than a "slight feeling of discomfort during activity" in either muscle group. No previous investigations have reported muscle soreness ratings of the quadriceps and hamstrings following three sets of 15 submaximal eccentric isokinetic contractions at the velocity and intensities specified in the present study. However, comparisons can be made with studies using slightly different protocols when exercising the same muscle groups. Fitzgerald et al. (53)

reported a peak pain rating of 1.12 cm in subjects who performed seven sets of ten repetitions at 90% of maximal concentric power using a velocity of 30°/sec. This value is similar to that reported by the 60% group and lower than that of the 80% group in the current study. Again, high intersubject variability, the slower velocity, or the difference in measurement instruments could have been a factor in the seemingly lower ratings described in their study given the exercise intensity and the number of repetitions performed.

Franklin et al. (56, 57) carried out two different investigations in which muscle soreness was rated after subjects performed three sets of 35 eccentric isokinetic contractions using the quadriceps and the hamstrings. Subjects exercised at a velocity of 120°/sec at an exercise intensity equal to 80% of their concentric peak torque . As in the present study, peak soreness in both muscle groups occurred 48 hours after the exercise bout. Although the measurement scale used by Franklin et al. was a ten point ordinal perception scale rather than the graphic pain rating scale, some comparisons can be made. The values for quadriceps soreness (.9 and 2.2 pain scale units) were similar to those reported by the 60% and 80% groups in the current investigation; however, the values reported for the hamstrings (4.1 and 6.7 pain scale units) were equal to or higher than those seen in the 100% group. These differences led the authors to conclude that the hamstrings are more vulnerable to muscle soreness than are the quadriceps. This finding was contradicted by the present study in which there was a tendency for the hamstrings to exhibit a higher soreness rating, but no significant differences existed between muscle groups at any of the three exercise intensities. These equivocal results are possibly explained by the difference in training velocities between the two studies. The higher velocity employed by Franklin et al. could have resulted in more stress being placed on the Type II fibers, and it is these fibers which exhibit the most severe damage following eccentric exercise (120). Since the hamstrings have a relatively greater proportion of Type II fibers than do the quadriceps, increased recruitment of these fibers could lead to a disproportionate increase in hamstring soreness which does not occur after slower eccentric isokinetic exercise (67).

It should be noted that some muscle soreness was reported by most subjects in the days immediately following the pretest which was performed one week prior to the exercise bout. This soreness was not measured, but many subjects commented on its presence when they reported for the second testing session. Therefore, the soreness response to the subsequent eccentric exercise bout may have been less than would have otherwise been observed. Several investigators (44, 121, 131, 132) have found that the development of muscle soreness is diminished after a repeated bout of the same exercise. Furthermore, Clarkson and Tremblay (21, 44, 121, 131, 132) showed that an adaptation also occurs when a prolonged exercise bout is preceded by exercise consisting of only one-third the number of contractions. Thus, although very few contractions were executed during the pretest (six maximal and two submaximal), they may have had the potential to partially attenuate the soreness response.

Muscle Soreness Perception

The current method of calculating soreness perception was used in two previous investigations by Hasson et al. (84, 85) to quantify and define the location of muscle soreness in the quadriceps. In both of these studies, quadriceps soreness was measured after subjects had performed bench stepping exercise for ten minutes at a rate of fifteen cycles per minute. Subjects were required to hold an additional load equivalent to ten percent of their body weight as they did the exercise. The perceived muscle soreness appears to be considerably higher in these studies than was reported here. However, this discrepancy is most likely related to the diameter of the probe used in each study. In the current study, the probe was 2 cm in diameter as described earlier in papers by Newham et al. (125) and Edwards et al. (45) In contrast, the probe used by Hasson et al. was only 2 mm in diameter (one tenth the size of the larger probe). Likewise, the mean soreness perception value at 48 hours post-exercise (.13) was more than ten times higher than that measured in the 100% group at the same time period (.01). These are reasonable results given that the previous investigators applied an equal amount of force to an exponentially smaller surface area. Soreness perception was considerably less in the 60% and 80% groups at all time periods. This is to be expected given the lower intensity of the exercise.

Muscle soreness perception in the hamstrings was not quantified prior to the current investigation. Perceived hamstring muscle soreness was similar to that reported for the quadriceps, confirming the results of the graphic pain rating assessment.

Location of Soreness

Several authors (45, 84, 85, 122, 125) have reported that soreness is most prevalent in the proximal-lateral thigh and in the distal vastus medialis following eccentric exercise of the quadriceps. The results of this study support their contention. Increased soreness in the distal, medial area is not unexpected because an electromyographic analysis of the quadriceps femoris performed by Fiebert et al. (51) revealed that the vastus medialis oblique is significantly more active than the rectus femoris and the vastus lateralis during eccentric isokinetic activation. Although no previous studies have described the muscle soreness response in the hamstrings, results of the current investigation did concur with others who reported that soreness was more prevalent in the distal portion of the muscle and around the tendinous insertion (5, 60).

Range of Motion

Decreased range of motion has often been cited as one indicator of muscle damage following eccentric contractions. Most authors who examined this phenomenon measured flexibility in either the biceps brachii (19, 92, 98) or the hamstrings (107, 174), both of which are biarticulate muscles. In the present study, hamstring range of motion remained unaffected in the submaximal groups, but it did decrease significantly over time in the 100% group. The greatest decline occurred 48 hours after the exercise bout, and values were still below baseline on the third post-exercise day. This finding is in accord with other investigators who have reported decreased range of motion on each post-exercise day following similar eccentric isokinetic exercise bouts (107, 174). No previous research has indicated whether or not significant range of motion deficits occur in conjunction with DOMS of the quadriceps muscles. Measurements of active knee flexion in the current investigation indicate that although the employed exercise protocol did induce significant muscle soreness in the 100% group, decreased quadriceps flexibility failed to materialize. This absence of restricted knee flexion range of motion might be explained by the fact that other than the rectus femoris, all muscles in the quadriceps group cross only one joint, and thus undergo fewer functional length changes than do muscles that act at two joints.

Maximal Voluntary Isometric Contraction

The eccentric isokinetic exercise bout did result in a relatively mild, yet significant, loss of maximal voluntary isometric strength in both the quadriceps and the hamstrings in the 80% and 100% groups. No such loss was experienced by the 60% group. The maximal exercise group exhibited a 19% decrease in quadriceps strength at 24 hours, while strength in the 80% group declined 11% in the same time period. The 80% group recovered their contraction ability more quickly than did the 100% group, as they almost regained full strength by the 48 hour point. In the maximal contraction group, reduction in muscle function persisted throughout the testing period although some recovery of strength (about 12 foot pounds) did occur by 72 hours post-exercise. Loss of strength in the 100% group was almost identical to that reported by Hasson et al. (84, 85) following bench stepping exercise of ten minutes duration while holding an additional ten percent of one's body weight. The recovery pattern in these two studies was also similar to that of the 100% group in the current investigation. In contrast, strength loss and recovery following five minutes of downhill running as previously reported by Donnelly et al. (38) is more in line with that exhibited by the 80% group in this study. Sargeant and Dolan (142) described strength deficits of much greater severity when subjects performed downhill walking until they collapsed. In their study, maximal voluntary contraction fell 45% by the 24 hour point and recovered only to 70% of baseline 72 hours later. Thus, it is evident that strength loss is proportionate to both the intensity and duration of the exercise performed.

Declines in hamstring strength were similar, but slightly greater than those seen in the quadriceps muscles in both the 80% and 100% groups, and the recovery patterns were also alike. This is not surprising since it is generally felt that muscle fiber damage is responsible for the muscle weakness seen following eccentric exercise, and Type II fibers experience a greater degree of fiber disruption (61, 74). Since the hamstrings have more Type II fibers than do the quadriceps, one would expect them to experience a greater decline in strength. It has also been noted that with the exception of Sargeant and Nolan (142) who imposed a very severe exercise regimen on their subjects, authors who examined muscle strength following eccentric exercise of the thigh musculature have described a much lower percentage of strength loss than that seen following eccentric upper extremity exercise involving the biceps brachii (19, 121, 132, 183). The current study is no exception. This could be because the exercise performed by the biceps brachii was of greater relative intensity than that employed in studies using the lower extremity. An alternative explanation is the relative size of the involved muscle mass . In the smaller biceps brachii, a greater percentage of the total muscle fibers are likely to be recruited during each contraction, and thus, more fibers could suffer damage.

Several investigators have previously stated that muscle soreness does not cause an inhibitory response which leads to the strength loss following an eccentric exercise bout because strength deficits are present before the soreness is most severe, and they remain after it has already declined (19, 74, 142). The current data support this contention as muscle soreness did not peak until 48 hours yet the most severe strength deficits were present 24 hours earlier.

Serum Creatine Kinase Activity

Large intersubject variability in serum creatine kinase response following eccentric exercise has been reported in the muscle soreness literature on numerous occasions (18, 19, 120, 122, 129). One source of CK variation is due to gender. The higher response exhibited by the male subjects in this investigation has been observed previously (152). However, Nosaka et al. (129) also documented CK values ranging from 298 IU/L to 8,092 IU/L following the performance of 24 maximal eccentric contractions of both forearms by twelve female subjects. Clarkson et al. (19) categorized subjects according to CK response following completion of two sets of 35 maximal eccentric forearm contractions. Three groups of CK responders were identified. The high responders had a peak increase of over 2,000 IU/L, the medium responders between 500 and 2,000 IU/L, and the low responders exhibited a peak of less than 500 IU/L. Equally large intersubject variation was seen in the present study, especially in the maximal exercise group. Six subjects (five females and one male) demonstrated a peak CK response greater than 2,000 IU/L. One male subject exhibited values which reached 16,722 IU/L 72 hours after the exercise bout. In contrast, peak values in three other subjects were less than 300 IU/L, and CK values in one subject whose measurement during the pre-exercise test session was high (470 IU/L), actually decreased over the four day measurement period.

Franklin et al. (57) reported mean CK values of 9,000 IU/L 48 hours after an eccentric isokinetic exercise bout in which subjects performed reciprocal eccentric contractions of the quadriceps and hamstring muscles. CK levels were still rising 72 hours post-exercise and reached 14,856 IU/L. Similar results were noted in the current study in that CK values continued to increase 72 hours after the eccentric exercise; however, mean values were considerably lower at all test sessions, even in the 100% group. This difference is not surprising because although the intensity of exercise performed by the maximal exercise group was higher in the present investigation, the velocity and number of repetitions were both lower than those utilized by Franklin et al.

The time course of CK elevation in this study was not in concert with the amount of muscle soreness perceived at the various test sessions. Maximal levels did not occur on the days when soreness was rated most severe, and CK levels continued to rise as soreness began to resolve. These results support an earlier assertion that although there is a relationship between serum CK elevation and delayed onset muscle soreness, the CK efflux is not the cause of the soreness (120, 122). Indeed, Newham et al. (122) have suggested that some type of pain producing substance might actually be acting as a precursor for the subsequent delayed rise in CK release.

No CK elevation was seen in either of the submaximal groups. This finding suggests that the submaximal eccentric isokinetic exercise bouts described in this investigation do not result in the degree of muscle damage required to trigger CK release. It is possible, however, that enzyme release in the submaximal groups was diminished by an adaptation response to the pretest and practice session performed the previous week. Several authors (19, 21, 40, 121, 130, 131, 147) have documented that the performance of one bout of eccentric exercise produces an adaptation such that the CK response is decreased when the same exercise is performed up to several months later. Clarkson et al. (19) state that this adaptation is apparent as soon as five days after exercise. The practice session consisted of fewer repetitions than were performed in the ensuing exercise bout, and the opposite limb was used in order to minimize the adaptive response. However, when combined with the maximal pretest, it could have abated the CK rise seen after the actual exercise session. Nosaka and Clarkson (130) reported significantly lower CK levels following a subsequent bout of eccentric exercise with the contralateral limb, although similar alterations were not observed in other indicators of muscle damage such as soreness, range of motion and strength. They concluded that the CK clearance rate is accelerated by initially high levels of the enzyme in the blood. This assertion would explain the systematic decline in CK values observed in some subjects who demonstrated higher than normal readings at the first measurement period. However, subjects with very low initial values also failed to exhibit a significant post-exercise CK efflux. Therefore, the alternative explanation that the submaximal exercise bouts were not of sufficient intensity to bring about substantial muscle damage must also be considered.

Summary

Performance of three sets of fifteen maximal eccentric isokinetic contractions of the quadriceps and hamstrings at a velocity of 60°/sec results in significant muscle soreness in both muscle groups and causes measurable increases in the objective indicators of muscle damage. However, the soreness response to an equal number of submaximal eccentric contractions performed at 60% or 80% of maximal effort is much less severe. Although this response may have been mildly attenuated by a protective adaptation brought on by the pretest performed one week earlier, the results of this study suggest that submaximal eccentric isokinetic training at the specified intensities places an individual at considerably less risk of suffering the consequences of exercise induced muscle damage than does maximal eccentric isokinetic training.

Part II

The mean concentric and eccentric peak torque values generated in this study exhibit torque-velocity relationships similar to those described in earlier isokinetic literature (23, 72, 77, 79). Mean concentric peak torque decreased as the velocity of contraction increased; however, eccentric peak torque remained constant across all velocities. Both concentric and eccentric peak torque were measured at 60^{o}/sec allowing direct comparison between their mean values. As expected, eccentric torque exceeded concentric torque in both the quadriceps and the hamstrings. Prior to training, eccentric torque values in both muscle groups were similar to those of other untrained subjects described by Griffin et al. (77).

Strength and Power Changes

Eccentric Peak Torque

The results of this study suggest that submaximal eccentric isokinetic training enhances peak torque gains in the quadriceps more effectively than does maximal training. Improvement in the 80% group exceeded that of the other two training groups at the training velocity of 60^{o}/sec. Gains in both submaximal groups surpassed those of the 100% group at all other test velocities. When averaged over all test velocities, eccentric peak torque increased 40% in both the 60% and the 80% groups. The group exerting maximal effort exhibited only a 30% torque increase. Interestingly, the 100% group showed no significant improvement at the 90^{o}/sec velocity. Perhaps a submaximal contraction intensity leads to greater facilitation of motor learning since neural factors play an important role in strength development, especially in the early stages of training (119).

Gains in both submaximal groups also exceeded those achieved in an earlier investigation by Duncan et al. (42) in which subjects trained their quadriceps using maximal eccentric isokinetic contractions. The improvement exhibited by their subjects was similar in magnitude to that recorded for the 100% group in the current investigation, although subjects in that study performed several fewer contractions per training session than was required by the current protocol. Following similar training, Tomberlin et al. (171) reported a 21% increase in eccentric peak torque which is less than that achieved by any training group in the present study.

Submaximal eccentric isokinetic training is also capable of promoting eccentric torque gains in the hamstrings within certain limits. Exercise at both submaximal intensities resulted in improvements equivalent to those of the 100% group when tested at the two slower velocities. However, at the faster speeds, 60% effort was incapable of rendering peak torque gains. In order to have overflow effects to higher eccentric velocities, it appears that one must work at an intensity of at least 80%. According to Friden et al. (59, 62), eccentric training results in structural changes in the muscle fiber architecture, primarily in Type II fibers. These adaptations produce an optimal overlay between the actin and myosin filaments and create better muscle fiber stretchability, which results in increased force production ability when these fibers are recruited. In accordance with the pattern of motor recruitment, a greater number of Type II fibers are recruited as the exercise speed and intensity increase. Therefore, fewer fibers are recruited during exercise performed at 60% of maximal effort, especially when performed at a slower velocity. As a result, training adaptations may not have occurred in a sufficient number of fast twitch fibers to effect an increase in eccentric peak torque at higher velocities. Again, the presence of a higher percentage of Type II fibers may result in the expression of this phenomenon in the hamstrings although it was not seen in the quadriceps.

The results of this study generally agree with the findings of previous investigators (9, 42, 108, 141) that eccentric isokinetic training at 60°/sec is not velocity-specific. With the exception of the 60% group, carryover to speeds 60 degrees above and 30 degrees below the training velocity was demonstrated. The magnitude of the torque gains was also similar to that reported in a previous study (141) in which the hamstrings were trained at a velocity of 120°/sec.

Concentric Peak Torque

Previous investigators (42, 62) have reported on the presence of mode-specificity following eccentric training. Some authors (62) contend that eccentric training causes a specific adaptation in muscle tissue which can augment eccentrically generated tension, but may not affect the tension produced during concentric contractions. Others suggest that neural mechanisms such as recruitment pattern efficiency, motor learning and inhibition of protective mechanisms, may contribute to one's ability to increase eccentric peak torque independent of any concentric gains (171). In contrast, the existence of physiologic overflow from the eccentric to the concentric contraction mode has also received support in the literature (105, 154). The results of the present investigation substantiate the concept of training mode-specificity. All training groups achieved significant eccentric peak torque gains in both muscle groups at two or more tested velocities, but only the 80% group exhibited improvement in concentric peak torque, and that increase was limited to one contraction speed.

These findings are in agreement with those of previous investigators (9, 42, 161, 171) who also failed to discern an increase in concentric torque after eccentric isokinetic training of the quadriceps. However, some eccentric isotonic training programs have resulted in significant improvements in concentric quadriceps strength (95, 96, 97). Duncan et al. (42) suggest that this discrepancy might be related to training velocity because subjects in their study trained at a high velocity (120°/sec) relative to that of isotonic training. However, the training velocity in the current investigation was much lower (60°/sec), and no concentric strength gains were achieved.

The absence of concentric peak torque gains in the hamstrings contradicts the results of earlier eccentric isokinetic training studies (9, 141). Two different investigators have reported increased concentric strength following eccentric training of the hamstring muscles at velocities of 60 and 120^{o}/sec. This disparity cannot be explained because subjects in one of these studies (9) performed fewer total contractions (three sets of six) at the same contraction velocity used in the current investigation. Additional research is needed to further examine this discrepancy.

Average Concentric Power

Power is defined as a muscle's ability to perform work in a specific period of time. Average power is calculated by dividing the total work performed in a specified number of contractions by the amount of time it takes to perform this work, and values are expressed in watts. Higher and more rapid force generation per contraction results in a greater power output. Within certain limits, average power has been shown to increase with contraction velocity (26, 30, 136, 140) but when isokinetic velocity exceeds 240^{o}/sec, the power curve levels off and even declines at the highest test speeds (30, 101). A similar power-velocity relationship is noted in the current investigation. Concentric power, averaged across training groups, was considerably higher at 180^{o} than it was at 60^{o}/sec. However, a slight decrease in power was observed at 300^{o}/sec, and even lower values were recorded at 450^{o}/sec.

It appears that eccentric isokinetic training must be performed at a fairly high percentage of maximal effort (at least 80%) to yield optimal improvement in the average concentric power of the hamstrings. Training at 60% effort did enhance power production at a speed of 60°/sec, but as the contraction speed increased, gains were limited to the 80% and 100% groups. Interestingly, only the 80% group improved significantly when tested at 180°/sec, the speed capable of generating the greatest power values. In contrast, eccentric isokinetic training of the quadriceps failed to yield improvement in average concentric power, regardless of the exercise intensity. The fact that these two muscle groups responded differently to training might be explained by the dissimilarity in fiber type population. The hamstrings have a higher percentage of muscle fibers adapted for high power output, and these Type II fibers are selectively recruited during eccentric exercise. The increased presence of fast twitch fibers could lead to a more pronounced adaptation than that seen in muscles with fewer Type II fibers.

Single Leg Hop for Distance

The lack of improvement in the single leg hop for distance is not surprising since two previous authors have shown that performance on this test is related more to concentric than eccentric quadriceps strength, and does not seem to correlate at all with strength in the hamstrings muscles (133, 162). Both of these investigators did detect a relationship between the single leg hop for distance test and concentric quadriceps peak torque, however, the two were not highly correlated ($r = 0.49$ and 0.47). Since the eccentric training protocol used in the current study failed to yield gains in concentric peak torque at any of the tested velocities, one would not expect concomitant improvement in the hop for distance test. However, Helbing et al. (87) did report significant improvement in the same test after subjects performed either three to five sets of 15 maximal eccentric isokinetic contractions at 120°/sec for five weeks. Surprisingly, this functional improvement was not accompanied by increased peak torque values. Subjects failed to demonstrate significant peak torque gains at any test velocity. Perhaps these equivocal results are explained by the fact that ankle range of motion, balance, and motor learning may play a larger role in performance on the single leg hop for distance test than does strength of the quadriceps and hamstrings.

Muscle Soreness Rating

Muscle soreness ratings using the graphic pain rating scale were performed prior to each exercise session throughout the eight week training period. Soreness ratings obtained during the initial week were similar to those provided by subjects in the first part of the study. However, muscle soreness disappeared by the beginning of the second week and thereafter, was not a problem in any training group. An equally rapid resolution of muscle soreness has been described by other investigators (9, 42) following repeated bouts of eccentric isokinetic exercise.

Several female subjects developed iatrogenic patellofemoral pain sometime during the course of the study. This problem primarily affected the 100% group although three subjects in the submaximal groups developed mild discomfort. Knee pain was experienced during eccentric contractions of the quadriceps, especially during the last ten degrees of terminal knee extension. Subjects also reported pain on stairs and during various other functional activities. In the 100% group, pain was sometimes a limiting factor in quadriceps torque production during the training sessions. Symptoms usually decreased significantly after four to six weeks of training. The development of these symptoms was somewhat surprising because previous eccentric isokinetic training studies involving the quadriceps made no mention of anterior knee pain (9, 42, 108, 161, 171, 182). Two of these studies (9, 42) utilized the same range of motion employed in the current investigation; however, fewer repetitions were performed at each training session. Furthermore, all subjects in both studies were male. In two other investigations, (108, 171) the range of motion was blocked ten degrees shy of full extension. Terminal knee extension was limited to prevent "locking out" of the knee. In the current study, the performance of an increased number of repetitions while working through the full range of motion seems to have placed excessive stress on the patellofemoral joint. In addition, patellofemoral alignment is often less optimal in females than it is in males which could partially explain the development of anterior knee pain by these female subjects.

Summary

Submaximal eccentric isokinetic exercise of the quadriceps and hamstrings was effective in improving eccentric peak torque. In order to achieve optimal gains at all velocities, training should be performed at 80% of maximal effort. Eccentric isokinetic training at a velocity of 60^{o}/sec resulted in significant carryover to both higher and lower eccentric velocities. However, the effects were mode-specific. Little or no improvement in concentric strength was seen in either muscle group at any training intensity.

Eccentric isokinetic training also failed to result in an increase in the average power of the quadriceps in any exercise group. An intensity not lower than 80% of maximal effort was required to achieve average power gains in the hamstrings, especially at the higher contraction velocities. The training protocol used in this study did not result in enhanced performance in the functional single leg hop for distance test.

Conclusions and Recommendations

The results of this investigation suggest that submaximal eccentric isokinetic training should be performed at 80% of maximal effort in order to achieve optimal strength and power gains in the quadriceps and hamstrings, while minimizing initial muscle damage and delayed onset muscle soreness. Although eccentric isokinetic exercise performed at 60% of maximal effort is also capable of increasing eccentric strength, the benefits of training at this intensity are more limited. In general, the 80% group achieved improvements greater than those exhibited by subjects who trained with maximal effort. Furthermore, maximal eccentric exercise as described in this investigation initially results in significant muscle soreness which may affect post-exercise athletic performance as well as discouraging one from continuing in a training program. In addition, maximal eccentric exercise of the quadriceps in the quantity prescribed here, resulted in the development of iatrogenic patellofemoral pain which interfered with training as well as daily function. It is recommended that the effects of submaximal eccentric isokinetic exercise continue to be explored at higher training velocities and in other muscle groups since it appears to be a highly effective tool for training and rehabilitation.

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APPENDIXES

APPENDIX A - TABLES

TABLE 1. Descriptive and Physical Characteristics of the Subjects - Part I

Variable	60% Group	80% Group	100% Group
n	10	10	10
Age (years)	27.1 ± 5.2	28.5 ± 7.2	31.3 ± 4.4
Height (cms)	165.4 ± 5.4	167.1 ± 10.5	163.8 ± 8.7
Weight (kgs)	60.7 ± 9.0	63.5 ± 20.7	64.6 ± 12.5

Values presented are means ± SD

TABLE 2. Descriptive and Physical Characteristics of the Subjects - Part II

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Age (years)	29.4 ± 6.1	27.1 ± 7.3	23.3 ± 5.2	23.4 ± 3.9
Height (cms)	172.7 ± 7.9	171.4 ± 7.6	163.8 ± 5.1	161.8 ± 7.5
Weight (kgs)	70.2 ±14.2	68.0 ±10.1	64.2 ±13.2	55.7 ±11.1

Values presented are means ± SD

TABLE 3. Pairwise Comparisons - Graphic Pain Rating Scale: Quadriceps

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (cm)	.85 ± .64^{A}	.97 ± .28^{A}	.90 ± .25^{A}
24 Hours (cm)	1.32 ± .22^{B}	1.56 ± .46^{B}	3.59 ± .44^{A}
48 Hours (cm)	1.01 ± .12^{C}	1.97 ± .43^{B}	4.61 ± .32^{A}
72 Hours (cm)	.91 ± .09^{B}	1.28 ± .25^{B}	2.75 ± .68^{A}

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 4. Pairwise Comparisons - Graphic Pain Rating Scale: Hamstrings

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (cm)	1.13 ± .16[A]	1.74 ± .42[A]	1.62 ± .34[A]
24 Hours (cm)	1.31 ± .21[B]	2.10 ± .46[B]	3.99 ± .47[A]
48 Hours (cm)	1.44 ± .28[C]	2.70 ± .50[B]	4.72 ± .42[A]
72 Hours (cm)	1.10 ± .09[B]	1.65 ± .22[B]	3.62 ± .58[A]

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 5. Pairwise Comparisons - Soreness Perception: Quadriceps

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest	.00007 ± .00006[A]	.00042 ± .00039[A]	.00009 ± .00009[A]
24 Hours	.00077 ± .00032[B]	.00270 ± .00166[A, B]	.00571 ± .00142[A]
48 Hours	.00056 ± .00023[B]	.00229 ± .00120[B]	.01007 ± .00341[A]
72 Hours	.00022 ± .00015[B]	.00060 ± .00042[A, B]	.00466 ± .00259[A]

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 6. Pairwise Comparisons - Soreness Perception: Hamstrings

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest	.00063 ± .00050[A]	.00054 ± .00027[A]	.00020 ± .00018[A]
24 Hours	.00085 ± .00052[A]	.00329 ± .00147[A]	.00265 ± .00037[A]
48 Hours	.00143 ± .00070[B]	.00285 ± .00063[B]	.00684 ± .00113[A]
72 Hours	.00087 ± .00058[B]	.00134 ± .00031[A, B]	.00409 ± .00153[A]

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 7. Pairwise Comparisons - Range of Motion: Quadriceps

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (degrees)	150.3 ± 0.9^{A}	153.2 ± 2.4^{A}	148.6 ± 1.9^{A}
24 Hours (degrees)	151.1 ± 1.1^{A}	152.2 ± 2.8^{A}	145.7 ± 2.5^{A}
48 Hours (degrees)	151.8 ± 1.5^{A}	152.9 ± 2.9^{A}	146.3 ± 2.3^{A}
72 Hours (degrees)	152.4 ± 1.5^{A}	152.3 ± 2.5^{A}	147.3 ± 2.3^{A}

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 8. Pairwise Comparisons - Range of Motion: Hamstrings

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (degrees)	29.1 ± 2.8^{A}	29.3 ± 3.7^{A}	32.3 ± 2.5^{A}
24 Hours (degrees)	29.1 ± 3.0^{B}	31.4 ± 3.0$^{A, B}$	39.1 ± 3.6^{A}
48 Hours (degrees)	29.3 ± 2.6^{B}	30.0 ± 3.1^{B}	43.1 ± 4.5^{A}
72 Hours (degrees)	25.6 ± 2.9^{B}	29.2 ± 4.2$^{A, B}$	36.6 ± 3.4^{A}

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 9. Pairwise Comparisons - Maximal Voluntary Isometric Strength: Quadriceps

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (ft lbs)	87.6 ± 4.8^{A}	98.6 ± 11.4^{A}	104.0 ± 9.5^{A}
24 Hours (ft lbs)	90.7 ± 5.3^{A}	88.3 ± 10.4^{A}	85.2 ± 9.4^{A}
48 Hours (ft lbs)	87.5 ± 5.6^{A}	94.6 ± 12.1^{A}	84.7 ± 8.9^{A}
72 Hours (ft lbs)	89.5 ± 5.5^{A}	99.7 ± 15.4^{A}	96.1 ± 9.4^{A}

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 10. Pairwise Comparisons - Maximal Voluntary Isometric Strength: Hamstrings

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (ft lbs)	40.4 ± 3.9^A	45.5 ± 7.1^A	47.5 ± 4.4^A
24 Hours (ft lbs)	40.2 ± 3.4^A	39.6 ± 4.9^A	35.3 ± 2.8^A
48 Hours (ft lbs)	41.7 ± 3.5^A	44.8 ± 7.2^A	35.9 ± 3.0^A
72 Hours (ft lbs)	42.1 ± 3.5^A	47.4 ± 6.6^A	36.4 ± 4.3^A

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 11. Pairwise Comparisons - Serum Creatine Kinase Activity

Variable	60% Group	80% Group	100% Group
n	10	10	10
Pretest (IU/L)	103.2 ± 31.2^{B}	226.6 ±100.2^{B}	306.1 ± 98.8^{A}
24 Hours (IU/L)	114.5 ± 26.1^{B}	181.0 ± 47.6^{B}	494.5 ± 164.9^{A}
48 Hours (IU/L)	98.3 ± 16.7^{B}	135.0 ± 28.4^{B}	1571.5 ± 617.4^{A}
72 Hours (IU/L)	84.2 ± 18.1^{B}	91.2 ± 14.7^{B}	3932.3 ± 1675.3^{A}

Values presented are means ± SE
Means with the same letter at each time period are not significantly different

TABLE 12. Adjusted Means Contrasts: Eccentric Peak Torque - Quadriceps: 30°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	9	10	10
Pretest (ft lbs)	149.1 ± 4.9	143.9 ± 4.9	157.4 ± 4.7	151.7 ± 4.9
Posttest (ft lbs)	158.5 ± 8.4	218.0 ± 8.4*	223.0 ± 8.0*†	202.9 ± 8.4**

* Significantly different from control group: $p < .0001$
** Significantly different from control group: $p < .0005$
† Significantly different from control group: $p < .0434$

TABLE 13. Adjusted Means Contrasts: Eccentric Peak Torque - Quadriceps: 60°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	9	10	10
Pretest (ft lbs)	156.5 ± 0.0	156.5 ± 0.0	156.5 ± 0.0	156.5 ± 0.0
Posttest (ft lbs)	161.3 ± 8.8	218.8 ± 8.8*	220.3 ± 8.4*†	196.5 ± 8.8**

* Significantly different from control group: $p < .0001$
** Significantly different from control group: $p < .0050$
† Significantly different from control group: $p < .0274$

TABLE 14. Adjusted Means Contrasts: Eccentric Peak Torque - Quadriceps: 90°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	9	10	10
Pretest (ft lbs)	150.4 ± 3.9	155.0 ± 4.0	150.2 ± 3.8	153.4 ± 4.0
Posttest (ft lbs)	168.9 ± 9.3	213.5 ± 9.4*†	210.6 ± 8.9††	188.1 ± 9.4

* Significantly different from control group: p < .0008
** Significantly different from control group: p < .0015
† Significantly different from 100% group: p < .0274
†† Significantly different from 100% group: p < .0431

TABLE 15. Adjusted Means Contrasts: Eccentric Peak Torque - Quadriceps: 120°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	9	10	10
Pretest (ft lbs)	148.6 ± 5.1	157.3 ± 5.1	152.9 ± 4.8	148.8 ± 5.1
Posttest (ft lbs)	158.6 ± 8.0	208.2 ± 8.0*†	210.1 ± 7.6*††	181.7 ± 8.0**

* Significantly different from control group: $p < .0001$
** Significantly different from control group: $p < .0295$
† Significantly different from 100% group: $p < .0140$
†† Significantly different from 100% group: $p < .0065$

TABLE 16. Adjusted Means Contrasts: Eccentric Peak Torque - Hamstrings: 30^{o}/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	68.5 ± 2.4	68.5 ± 2.4	67.9 ± 2.4	69.6 ± 2.4
Posttest (ft lbs)	73.3 ± 4.7	88.4 ± 4.6*	99.2 ± 4.6**	94.5 ± 4.8†

* Significantly different from control group: $p < .0136$
** Significantly different from control group: $p < .0002$
† Significantly different from control group: $p < .0021$

TABLE 17. Adjusted Means Contrasts: Eccentric Peak Torque - Hamstrings: 60°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	73.1 ± 0.0	73.1 ± 0.0	73.1 ± 0.0	73.1 ± 0.0
Posttest (ft lbs)	78.3 ± 4.5	89.5 ± 4.5*	98.9 ± 4.4**	97.8 ± 4.6†

* Significantly different from control group: $p < .0412$
** Significantly different from control group: $p < .0014$
† Significantly different from control group: $p < .0031$

TABLE 18. Adjusted Means Contrasts: Eccentric Peak Torque - Hamstrings: 90°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	72.0 ± 2.1	69.8 ± 2.1	69.4 ± 2.1	69.8 ± 2.2
Posttest (ft lbs)	79.1 ± 4.9	79.5 ± 4.8	98.0 ± 4.8*†	95.8 ± 5.0**††

* Significantly different from control group: $p < .0049$
** Significantly different from control group: $p < .0135$
† Significantly different from 60% group: $p < .0051$
†† Significantly different from 60% group: $p < .0130$

TABLE 19. Adjusted Means Contrasts: Eccentric Peak Torque - Hamstrings: 120°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	72.4 ± 3.1	68.8 ± 3.0	72.7 ± 3.0	65.4 ± 3.1
Posttest (ft lbs)	77.1 ± 4.8	75.5 ± 4.6	97.2 ± 4.6 *†	94.1 ± 4.8 **††

* Significantly different from control group: $p < .0023$
** Significantly different from control group: $p < .0096$
† Significantly different from 60% group: $p < .0011$
†† Significantly different from 60% group: $p < .0045$

TABLE 20. Adjusted Means Contrasts: Concentric Peak Torque - Quadriceps: 60°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	107.6 ± 5.2	110.8 ± 5.1	112.6 ± 5.0	102.9 ± 5.3
Posttest (ft lbs)	110.2 ± 5.8	120.3 ± 5.7	122.7 ± 5.7	113.4 ± 5.9

No group significantly different from control group

TABLE 21. Adjusted Means Contrasts: Concentric Peak Torque - Quadriceps: 180°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	71.4 ± 4.0	72.8 ± 3.9	74.5 ± 3.9	68.7 ± 4.1
Posttest (ft lbs)	76.2 ± 4.9	76.6 ± 4.8	82.0 ± 4.7	74.1 ± 5.0

No group significantly different from control group

TABLE 22. Adjusted Means Contrasts: Concentric Peak Torque - Quadriceps: 300°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	57.0 ± 3.4	56.2 ± 3.3	58.2 ± 3.3	51.9 ± 3.4
Posttest (ft lbs)	61.0 ± 3.8	57.8 ± 3.7	60.3 ± 3.7	55.4 ± 3.9

No group significantly different from control group

TABLE 23. Adjusted Means Contrasts: Concentric Peak Torque - Quadriceps: 450°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	45.2 ± 2.3	44.8 ± 2.2	51.5 ± 2.2	42.6 ± 2.3
Posttest (ft lbs)	49.1 ± 3.3	46.3 ± 3.2	53.4 ± 3.2	46.3 ± 3.3

No group significantly different from control group

TABLE 24. Adjusted Means Contrasts: Concentric Peak Torque - Hamstrings: 60°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	50.2 ± 3.3	52.4 ± 3.2	55.7 ± 3.2	51.0 ± 3.3
Posttest (ft lbs)	53.0 ± 3.3	59.2 ± 3.2	63.5 ± 3.2*	58.1 ± 3.3

* Significantly different from control group: $p < .0145$

TABLE 25. Adjusted Means Contrasts: Concentric Peak Torque - Hamstrings: 180°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	38.8 ± 2.5	36.1 ± 2.4	40.7 ± 2.4	35.8 ± 2.5
Posttest (ft lbs)	39.5 ± 2.6	40.3 ± 2.6	46.6 ± 2.6	43.5 ± 2.7

No group significantly different from control group

TABLE 26. Adjusted Means Contrasts: Concentric Peak Torque - Hamstrings: 300^{o}/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	38.8 ± 2.5	36.1 ± 2.4	40.7 ± 2.4	35.8 ± 2.5
Posttest (ft lbs)	39.5 ± 2.6	40.3 ± 2.6	46.6 ± 2.6	43.5 ± 2.7

No group significantly different from control group

TABLE 27. Adjusted Means Contrasts: Concentric Peak Torque - Hamstrings: 450°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (ft lbs)	28.3 ± 1.9	21.3 ± 2.1	27.1 ± 2.3	25.7 ± 2.7
Posttest (ft lbs)	25.9 ± 1.9	24.1 ± 2.1	27.4 ± 2.3	29.6 ± 2.7

No group significantly different from control group

TABLE 28. Adjusted Means Contrasts: Average Concentric Power - Quadriceps: 60^o/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	92.6 ± 5.4	90.8 ± 5.3	98.4 ± 5.2	89.0 ± 5.5
Posttest (watts)	96.8 ± 5.1	101.8 ± 4.9	104.7 ± 4.8	102.8 ± 5.0

No group significantly different from control group

TABLE 29. Adjusted Means Contrasts: Average Concentric Power - Quadriceps: 180°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	163.4 ± 10.0	163.1 ± 9.8	169.0 ± 9.7	155.8 ± 10.2
Posttest (watts)	169.3 ± 11.7	172.5 ±11.4	189.9 ±11.3	172.6 ± 11.9

No group significantly different from control group

TABLE 30. Adjusted Means Contrasts: Average Concentric Power - Quadriceps: 300°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	163.6 ± 10.0	155.3 ± 11.9	172.0 ± 11.8	151.8 ± 12.4
Posttest (watts)	165.3 ± 14.2	166.3 ± 13.9	189.8 ± 13.7	176.3 ± 14.5

No group significantly different from control group

TABLE 31. Adjusted Means Contrasts: Average Concentric Power - Quadriceps: 450°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	128.1 ± 16.8	141.6 ± 16.3	114.5 ± 19.2	119.4 ± 23.9
Posttest (watts)	138.4 ± 20.5	124.9 ± 19.8	119.6 ± 23.3	128.7 ± 29.1

No group significantly different from control group

TABLE 32. Adjusted Means Contrasts: Average Concentric Power - Hamstrings: 60°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	48.6 ± 3.8	45.4 ± 3.7	52.7 ± 3.7	48.6 ± 3.8
Posttest (watts)	49.1 ± 3.0	56.3 ± 3.0*	61.8 ± 3.0**	59.7 ± 3.1†

* Significantly different from control group: $p < .0479$
** Significantly different from control group: $p < .0025$
† Significantly different from control group: $p < .0115$

TABLE 33. Adjusted Means Contrasts: Average Concentric Power - Hamstrings: 180°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	86.6 ± 8.6	80.7 ± 8.4	89.9 ± 8.4	78.0 ± 8.7
Posttest (watts)	87.5 ± 7.2	85.7 ± 7.0	113.0 ± 7.0*†§	104.5 ± 7.2

* Significantly different from control group: $p < .0077$
† Significantly different from 100% group: $p < .0363$
§ Significantly different from 60% group: $p < .0115$

TABLE 34. Adjusted Means Contrasts: Average Concentric Power - Hamstrings: 300°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	79.5 ± 8.1	66.8 ± 7.9	78.0 ± 7.9	75.1 ± 8.2
Posttest (watts)	67.7 ± 9.5	79.1 ± 9.3	107.0 ± 9.3*†	100.6 ± 7.2**

* Significantly different from control group: $p < .0028$
** Significantly different from control group: $p < .0120$
† Significantly different from 60% group: $p < .0204$

TABLE 35. Adjusted Means Contrasts: Average Concentric Power - Hamstrings: 450°/Second

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (watts)	56.5 ± 9.5	41.3 ±10.2	63.1 ± 11.1	55.3 ±13.3
Posttest (watts)	48.2 ± 10.9	52.6 ±11.8	69.9 ± 12.8	70.1 ±15.4

No group significantly different from control group

TABLE 36. Adjusted Means Contrasts: Single Leg Hop for Distance Test

Variable	Control Group	60% Group	80% Group	100% Group
n	10	10	10	10
Pretest (cm)	114.4 ± 7.7	115.1 ± 8.0	126.7 ± 7.5	126.5 ± 7.9
Posttest (cm)	115.1 ± 8.4	126.4 ± 8.8	132.9 ± 8.2	133.3 ± 8.4

No group significantly different from control group

APPENDIX B - FIGURES

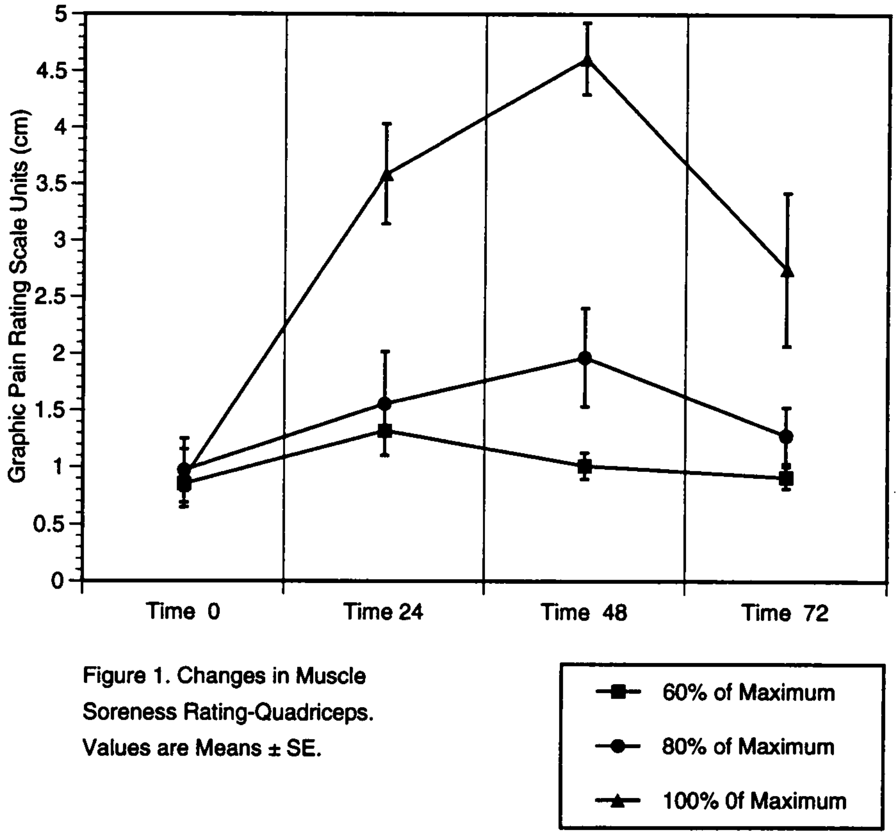


Figure 1. Changes in Muscle Soreness Rating-Quadriceps. Values are Means ± SE.

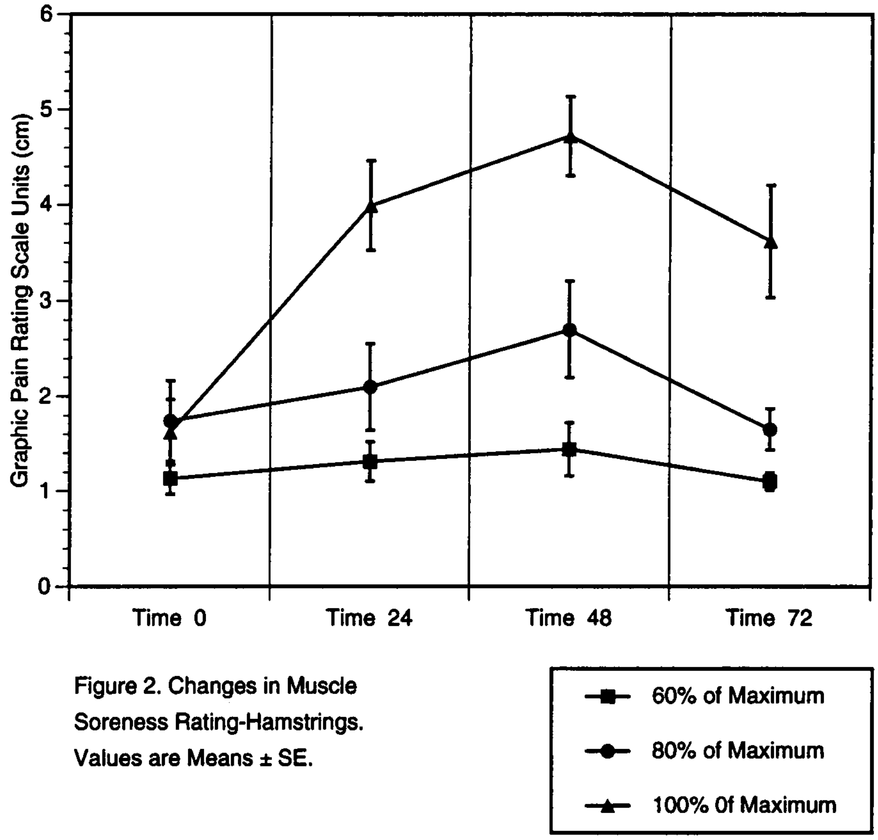


Figure 2. Changes in Muscle Soreness Rating-Hamstrings. Values are Means ± SE.

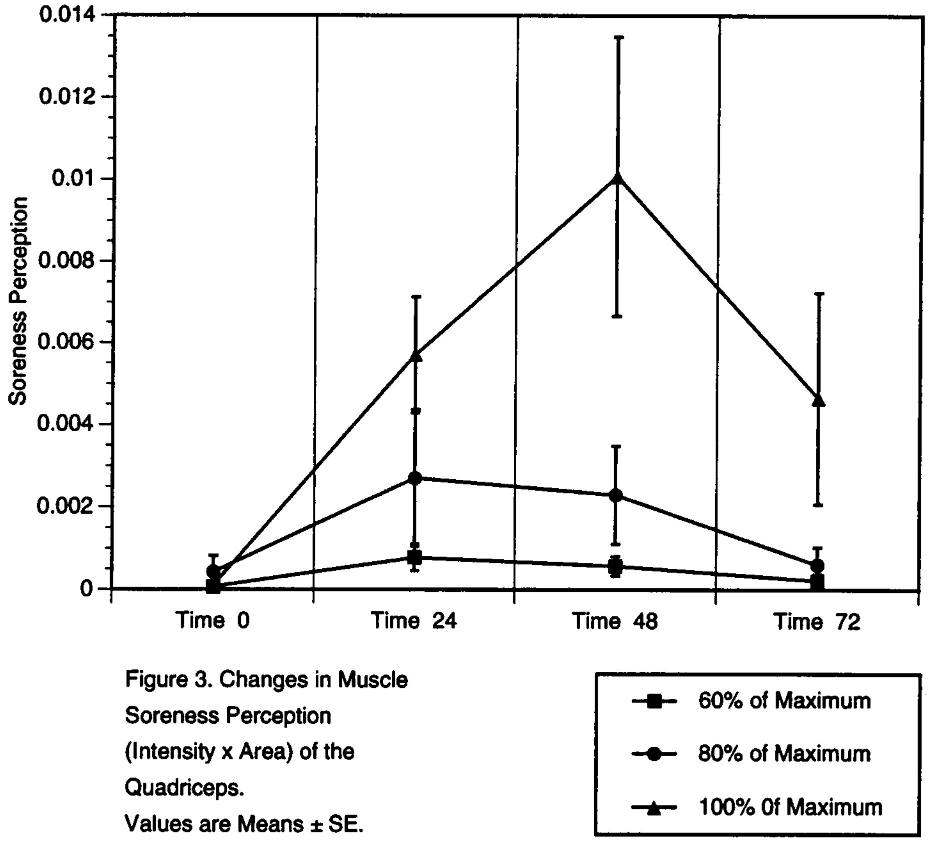


Figure 3. Changes in Muscle Soreness Perception (Intensity x Area) of the Quadriceps.
Values are Means ± SE.

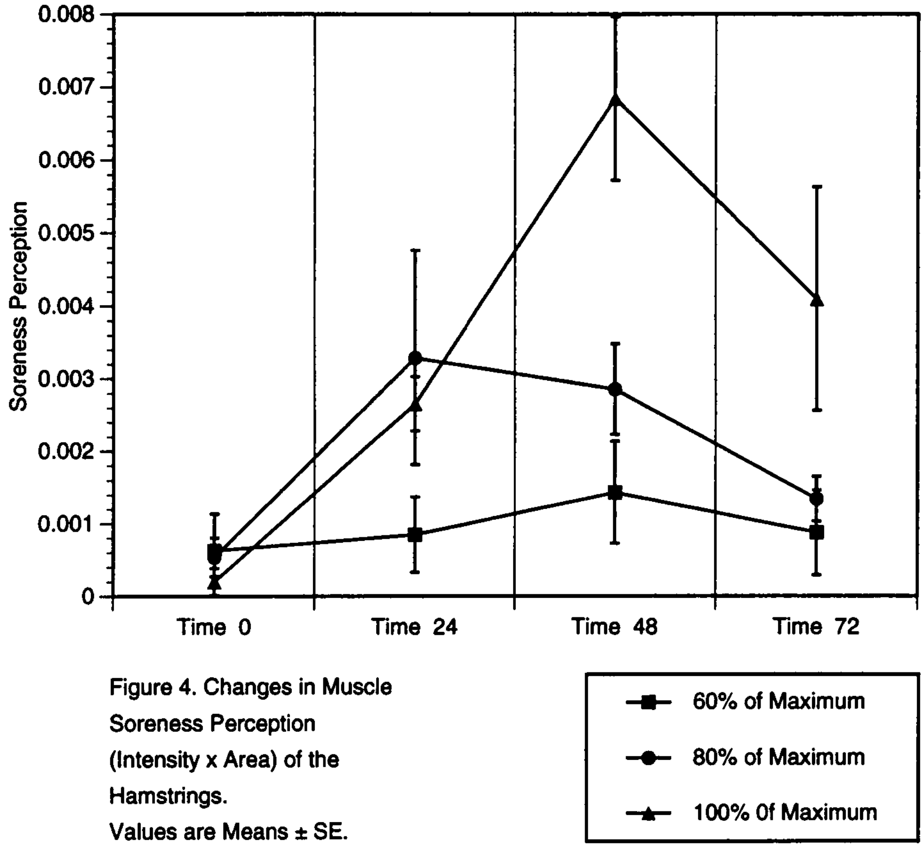


Figure 4. Changes in Muscle Soreness Perception (Intensity x Area) of the Hamstrings.
Values are Means ± SE.

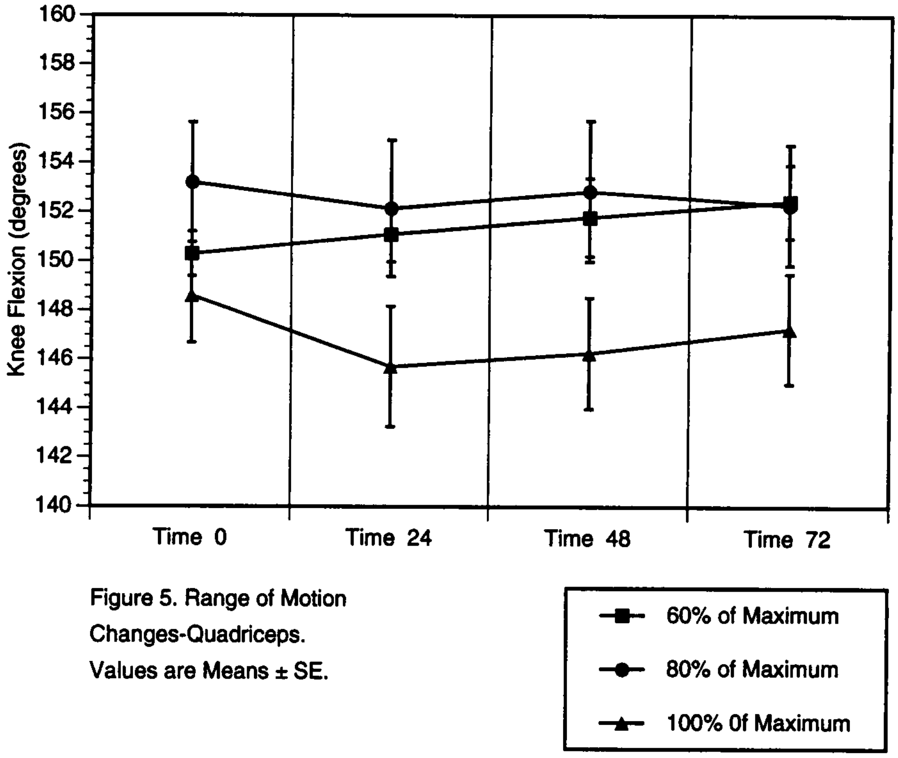


Figure 5. Range of Motion Changes-Quadriceps. Values are Means ± SE.

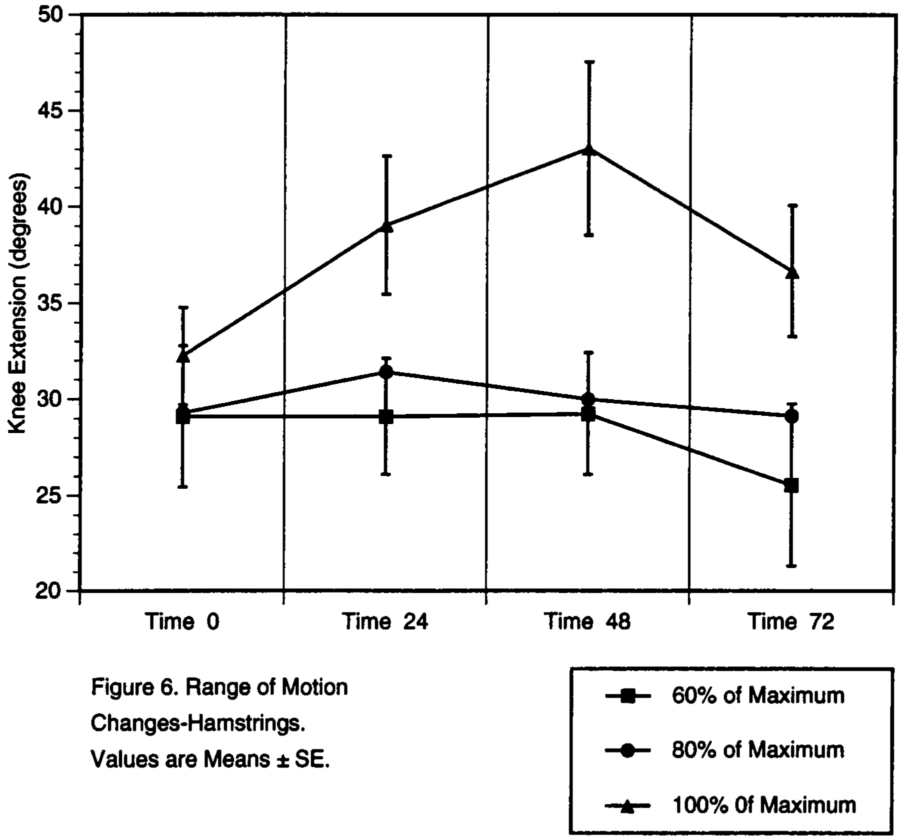


Figure 6. Range of Motion Changes-Hamstrings. Values are Means ± SE.

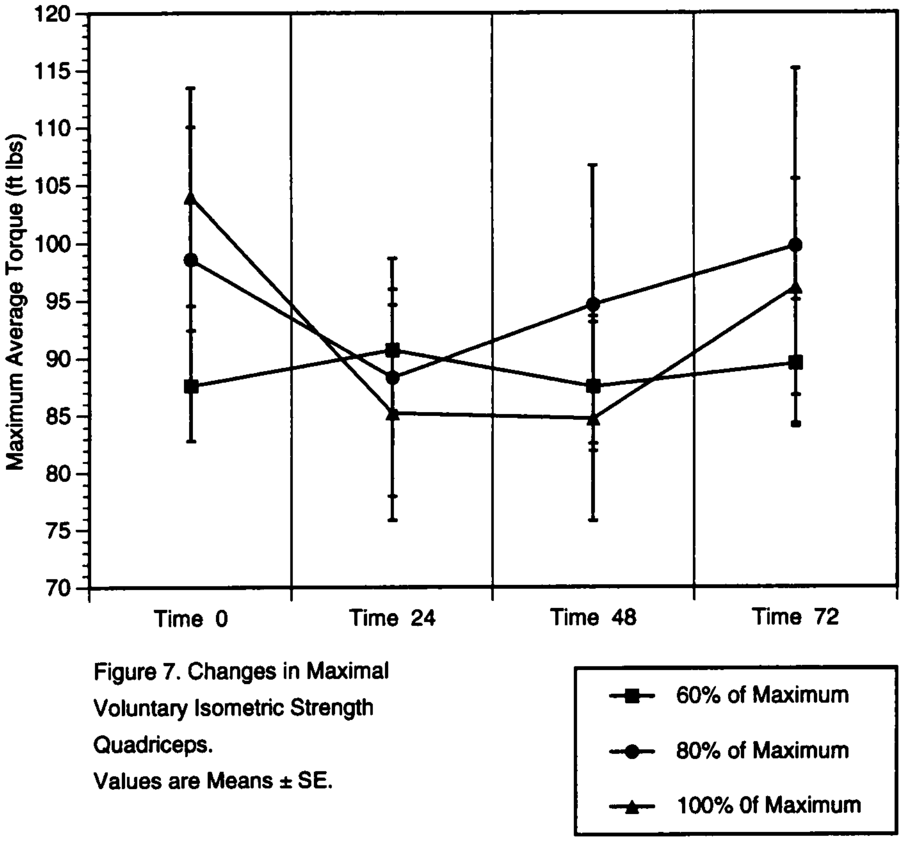


Figure 7. Changes in Maximal Voluntary Isometric Strength Quadriceps.
Values are Means ± SE.

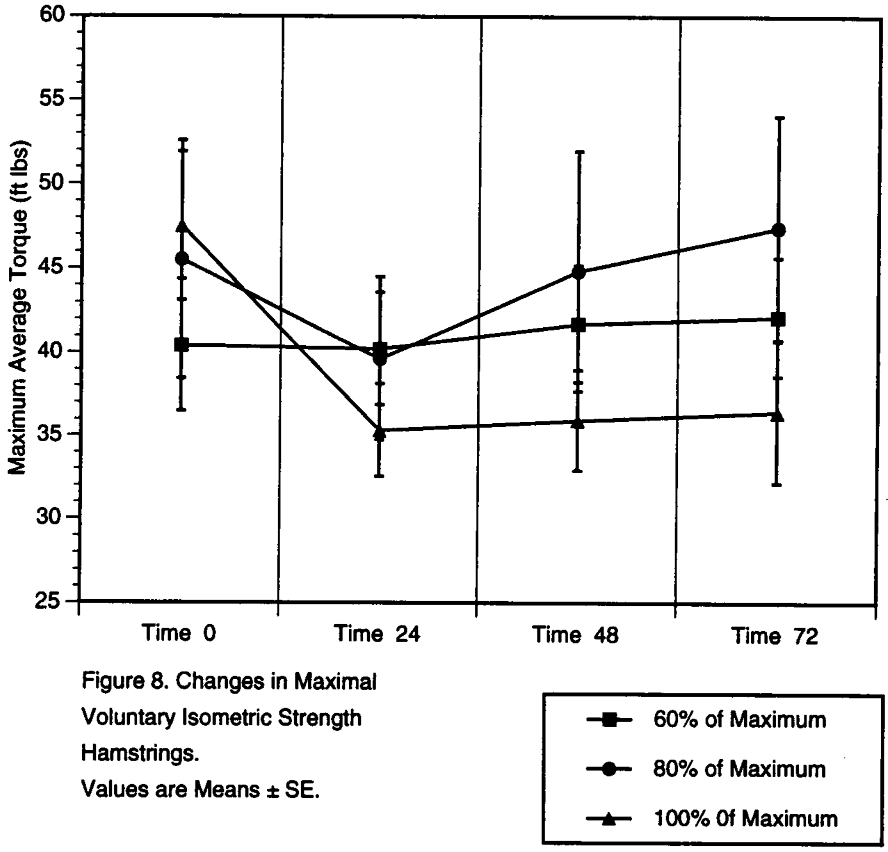


Figure 8. Changes in Maximal
Voluntary Isometric Strength
Hamstrings.
Values are Means ± SE.

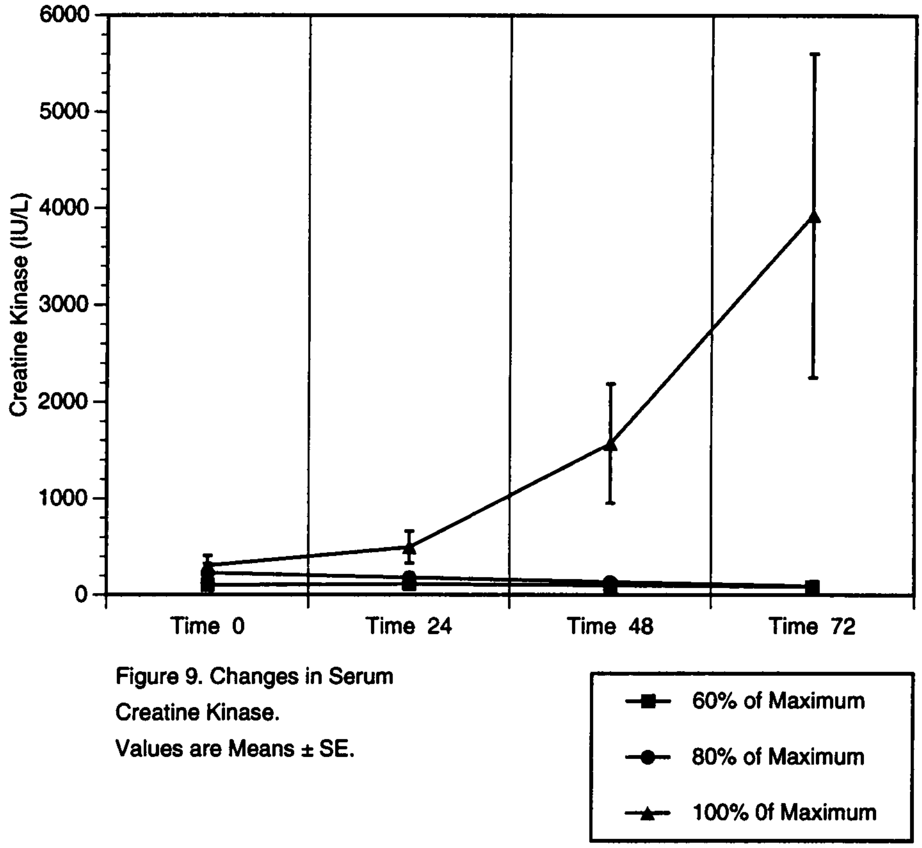


Figure 9. Changes in Serum Creatine Kinase.
Values are Means ± SE.

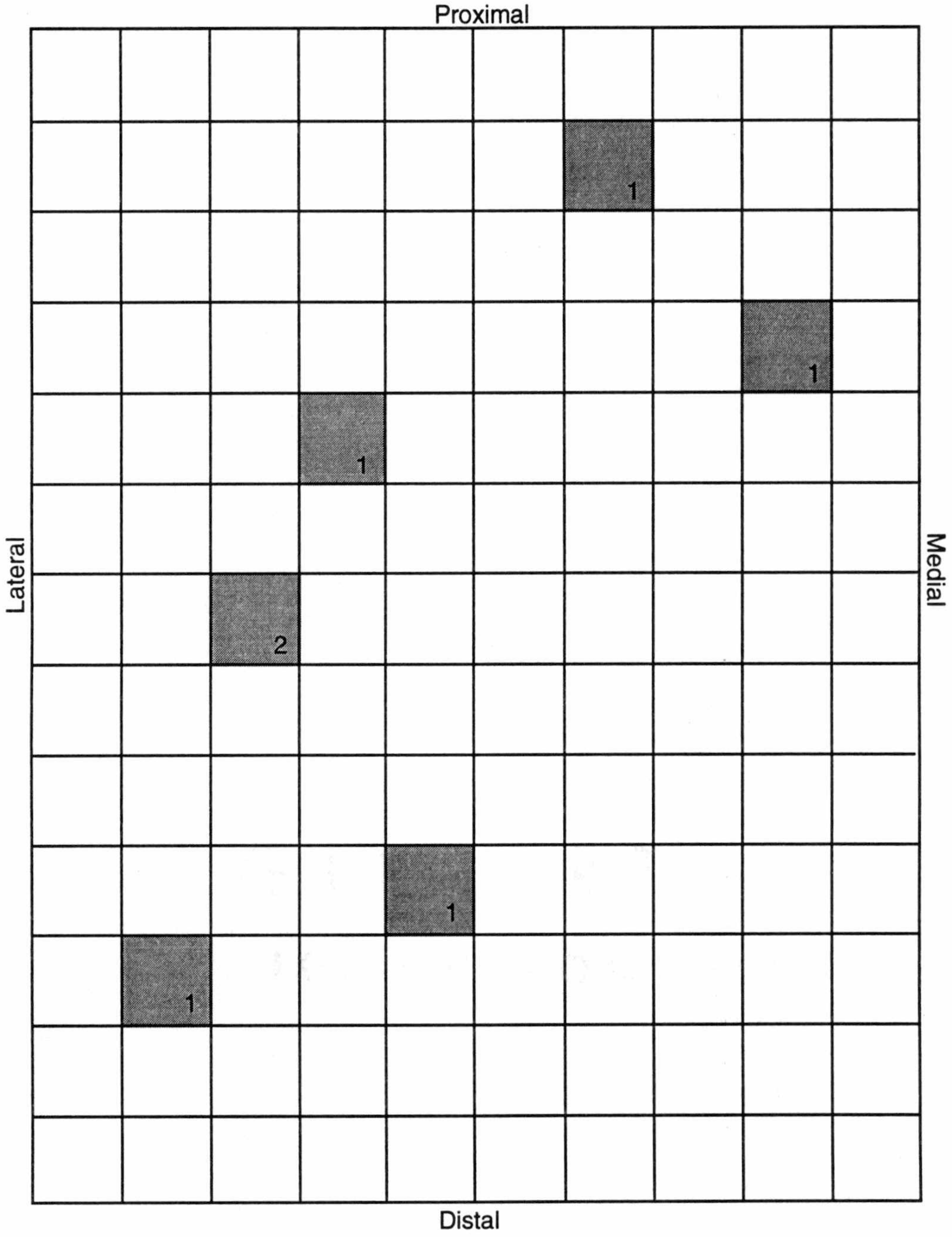


Figure 10-a. Soreness Perception - Quadriceps
60% Group: Pretest

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

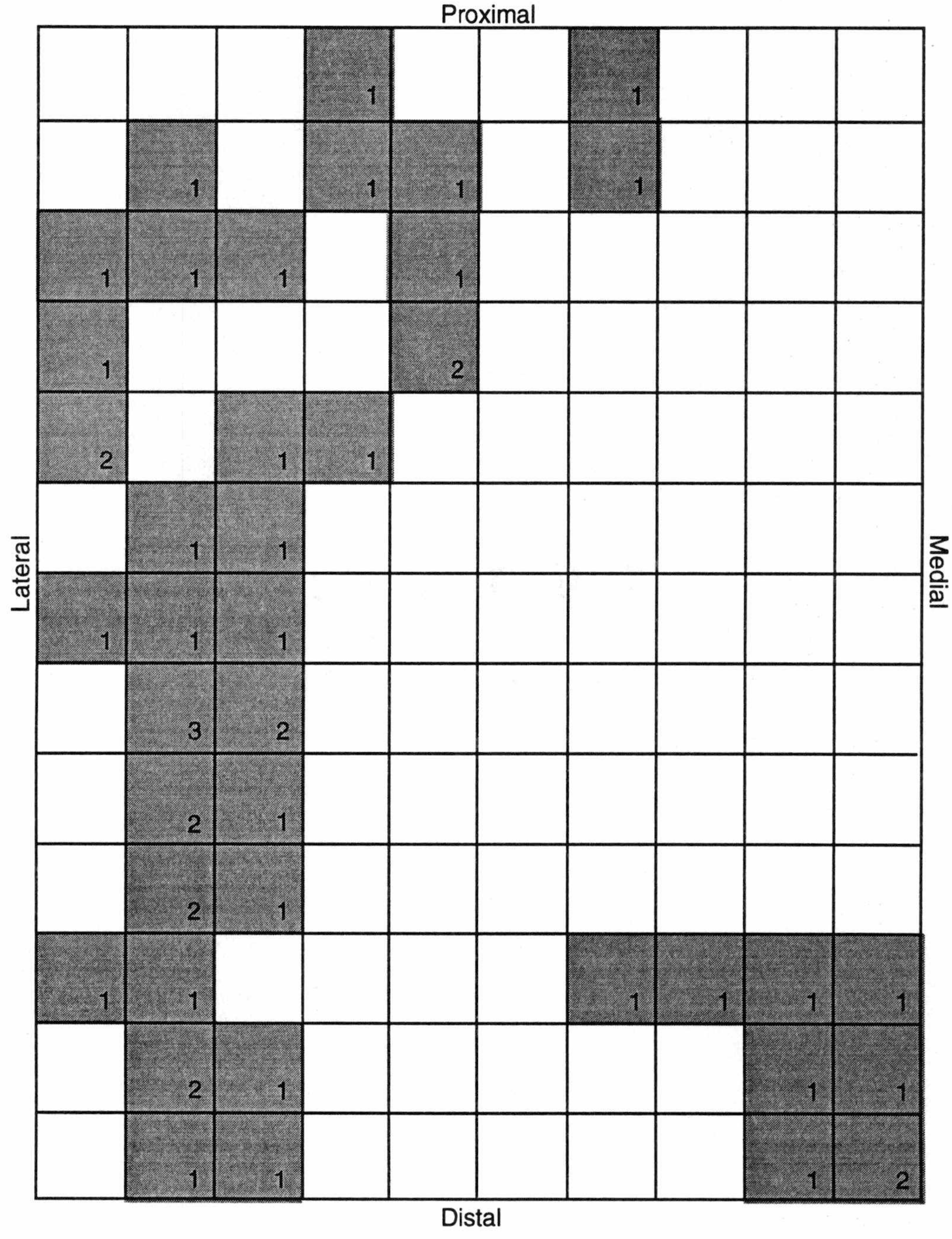


Figure 10-b. Soreness Perception - Quadriceps
60% Group: 24 Hours

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

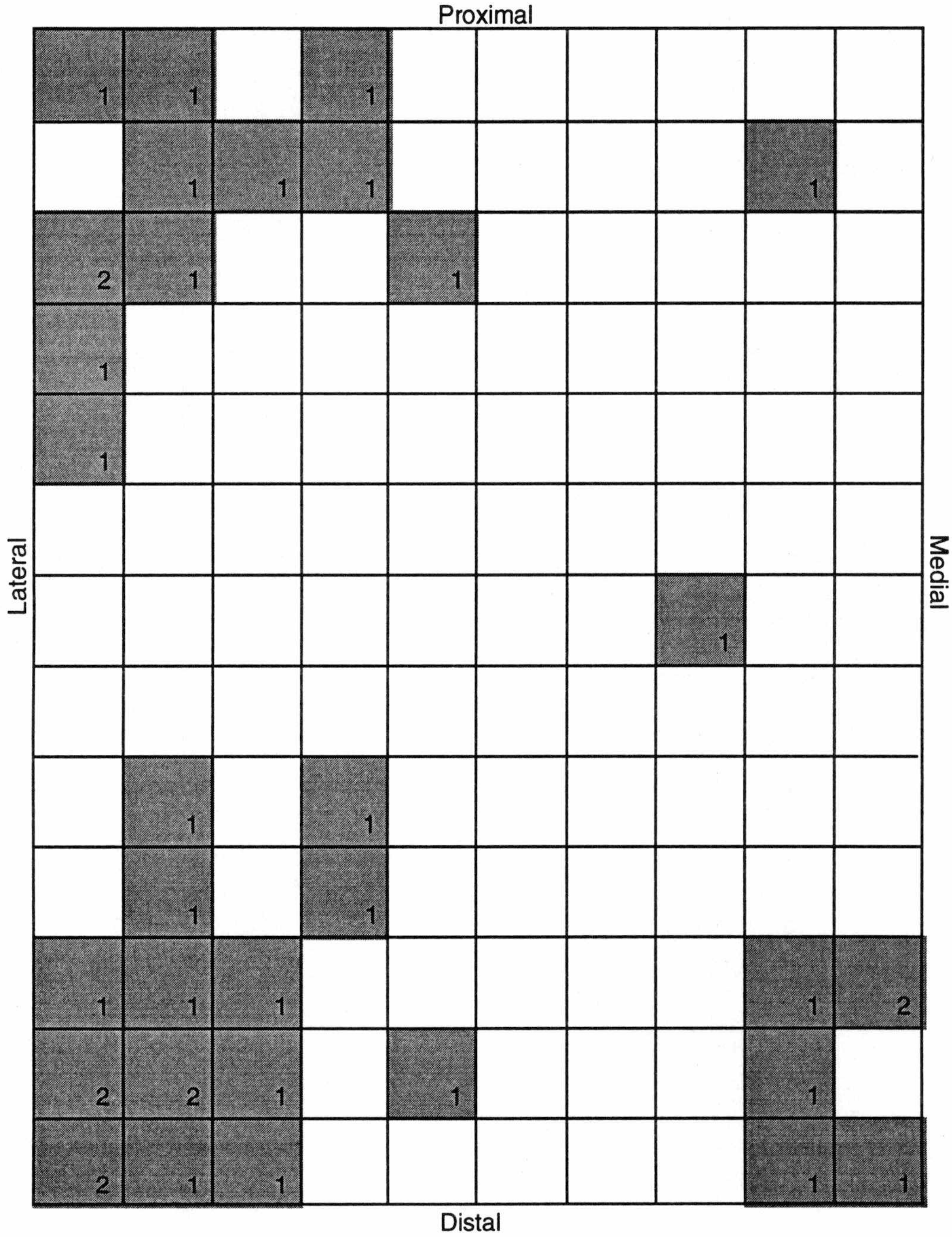


Figure 10-c. Soreness Perception - Quadriceps
60% Group: 48 Hours

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

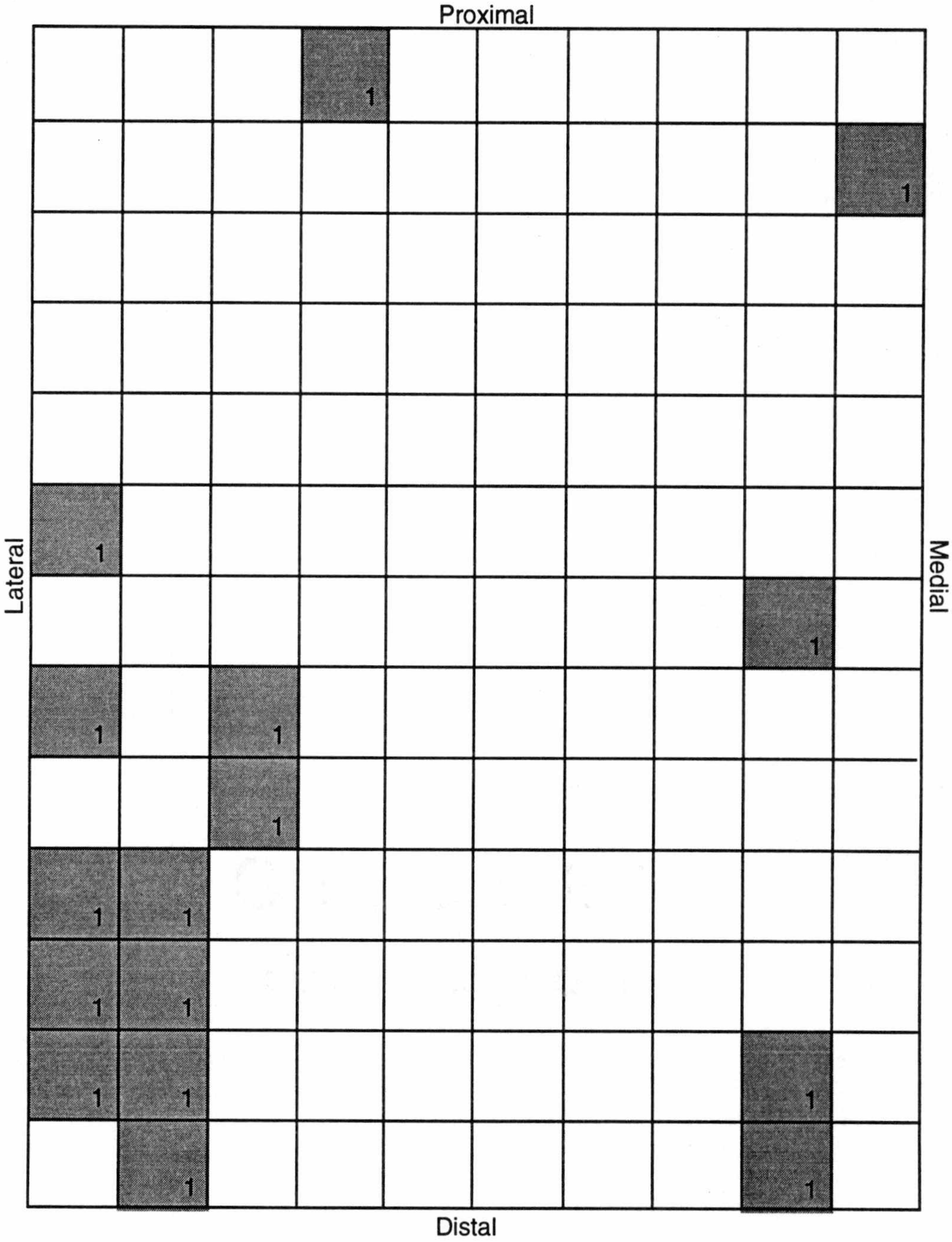


Figure 10-d. Soreness Perception - Quadriceps
60% Group: 72 Hours

LEGEND

- No Soreness
- Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

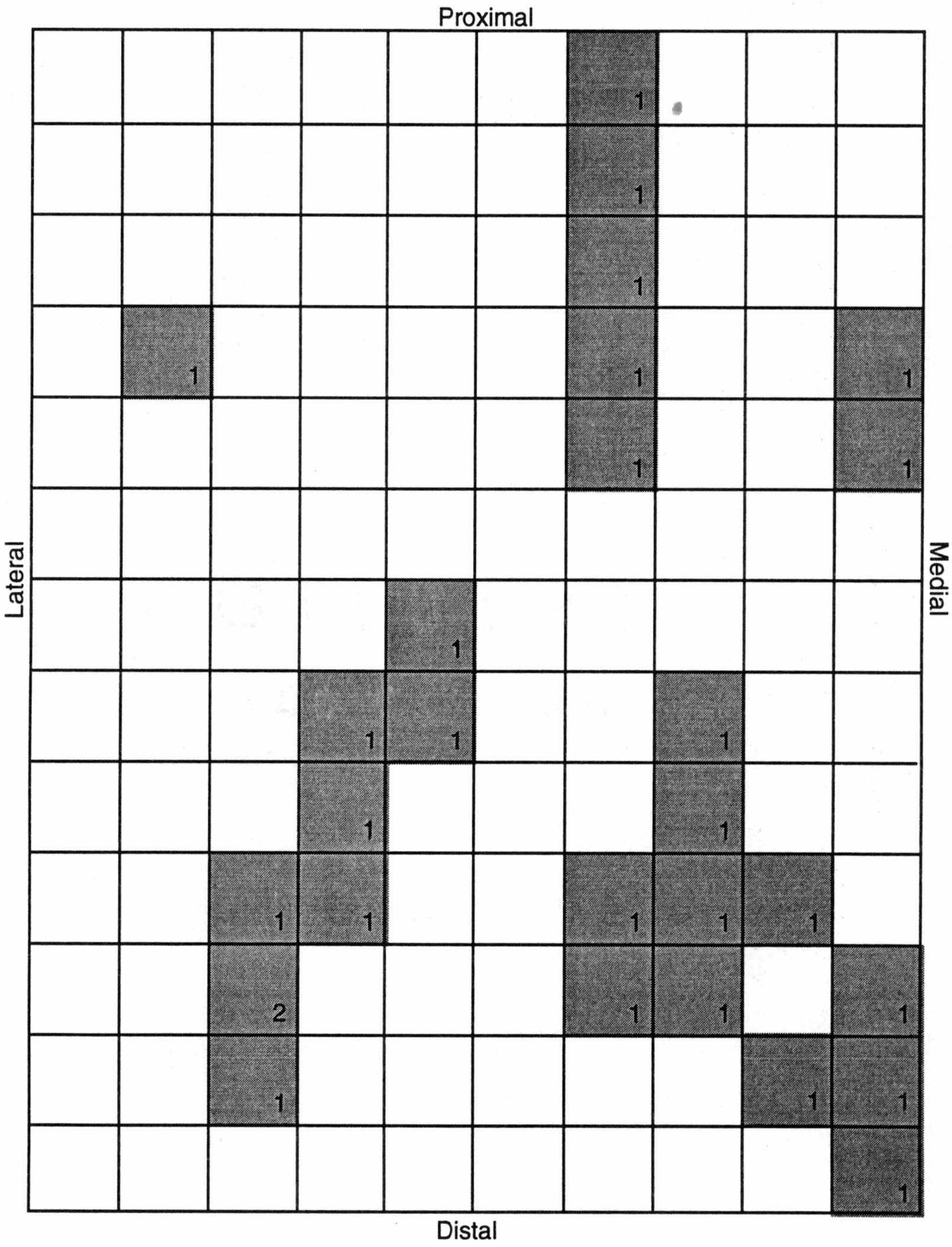


Figure 10-e. Soreness Perception - Quadriceps
80% Group: Pretest

LEGEND

- No Soreness
- Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

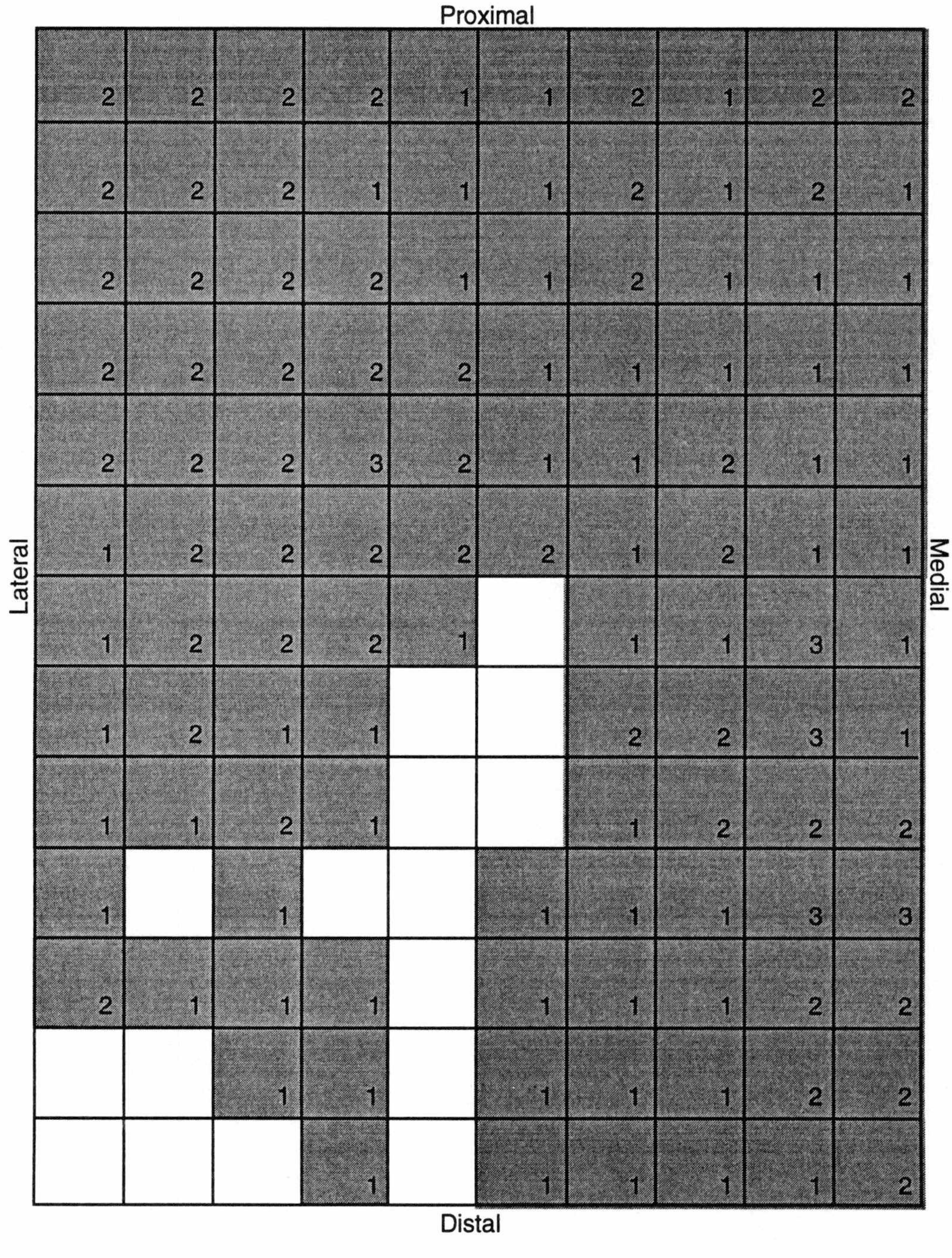


Figure 10-f. Soreness Perception - Quadriceps
80% Group: 24 Hours

LEGEND

- No Soreness
- Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

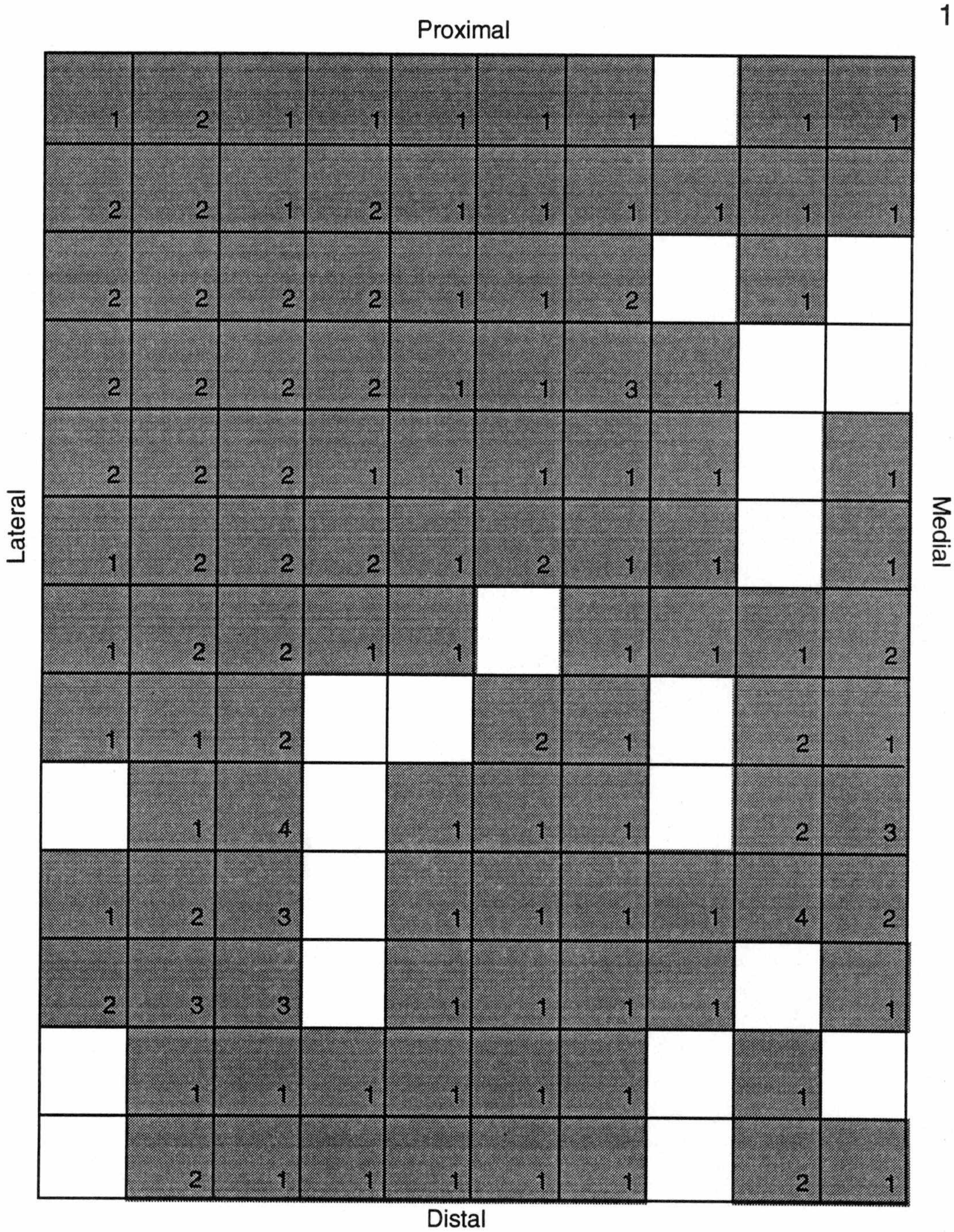


Figure 10-g. Soreness Perception - Quadriceps
80% Group: 48 Hours

LEGEND

No Soreness

Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

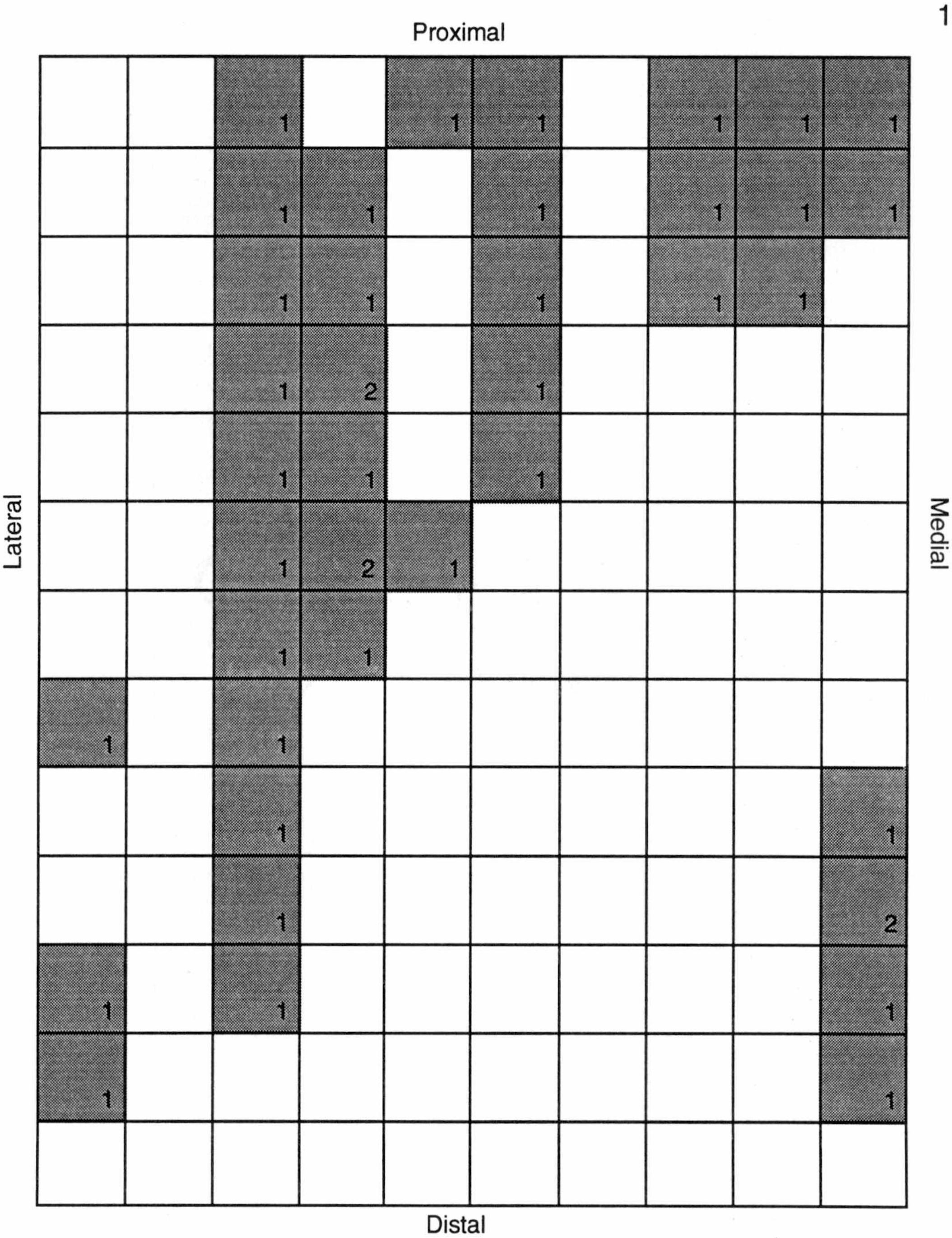


Figure 10-h. Soreness Perception - Quadriceps
80% Group: 72 Hours

LEGEND

No Soreness

Mean Soreness
Below Threshold

No (1, 2 . . .) = Total Persons with
Soreness Per Site out of 10
Persons Tested

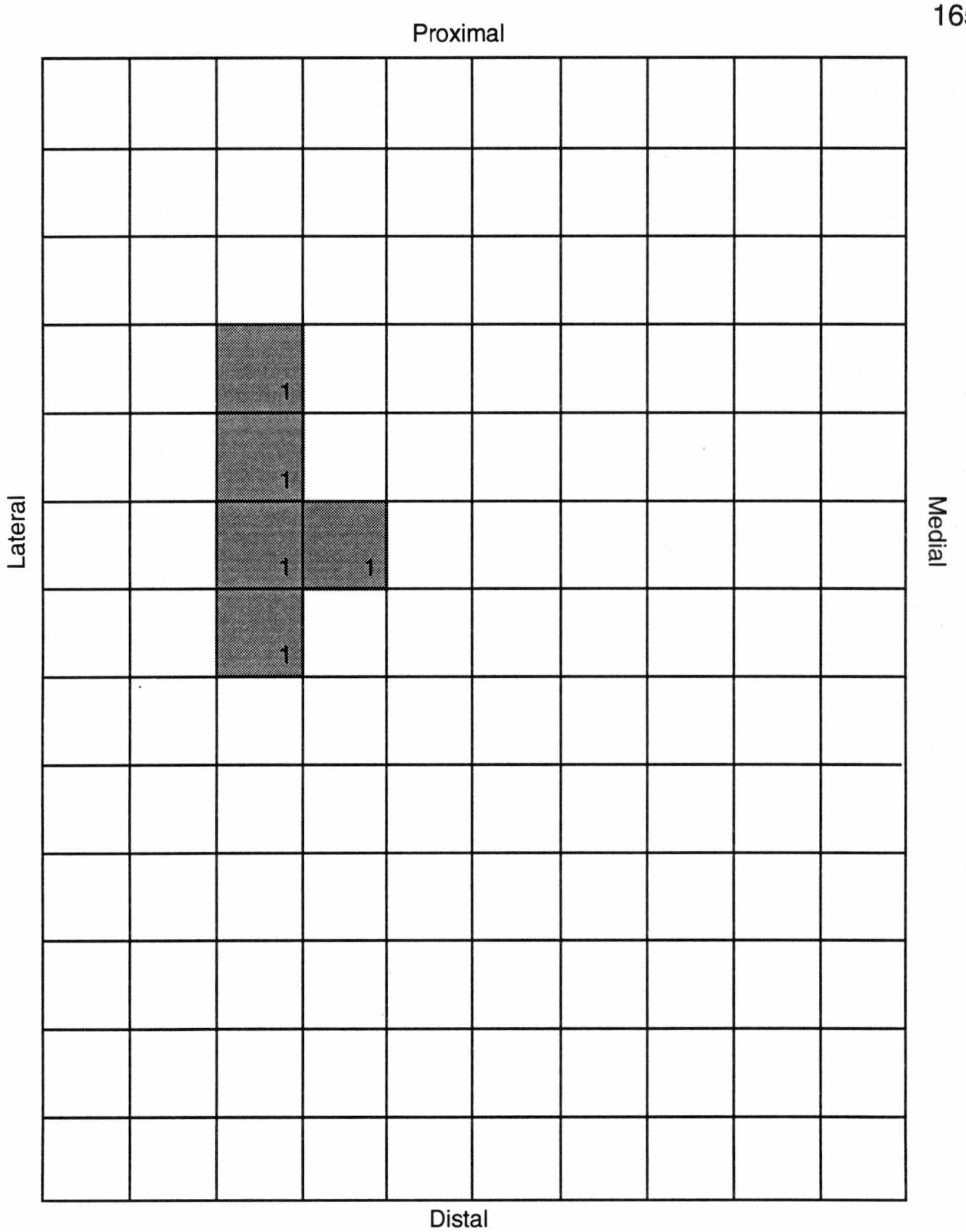


Figure 10-i. Soreness Perception - Quadriceps
100% Group: Pretest

LEGEND

No Soreness

Mean Soreness
Below Threshold

No (1, 2 . . .) = Total Persons with
Soreness Per Site out of 10
Persons Tested

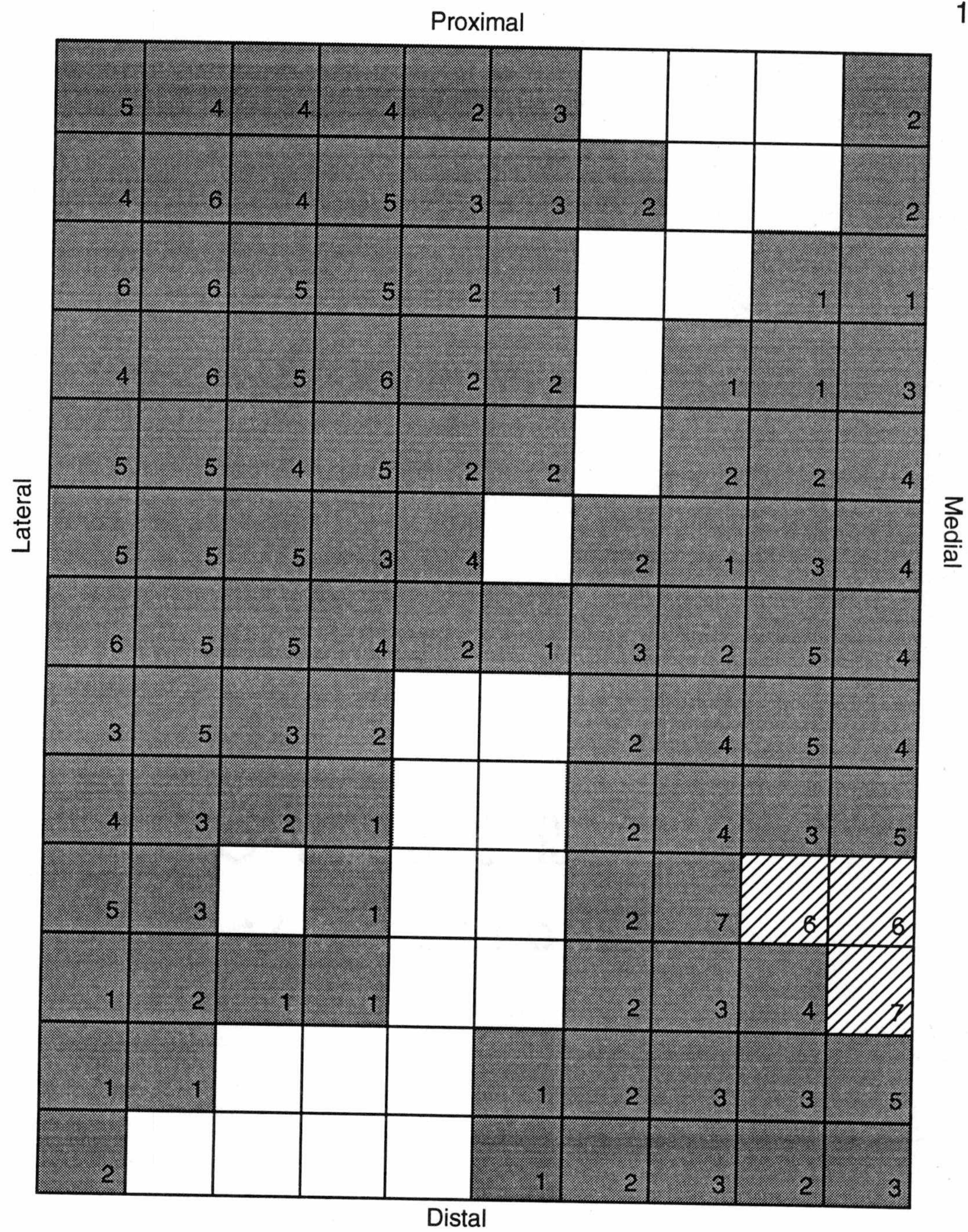


Figure 10-j. Soreness Perception - Quadriceps
100% Group: 24 Hours

LEGEND

- ☐ No Soreness
- ■ Mean Soreness Below Threshold
- ▨ Mean Soreness at 50-58 N

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

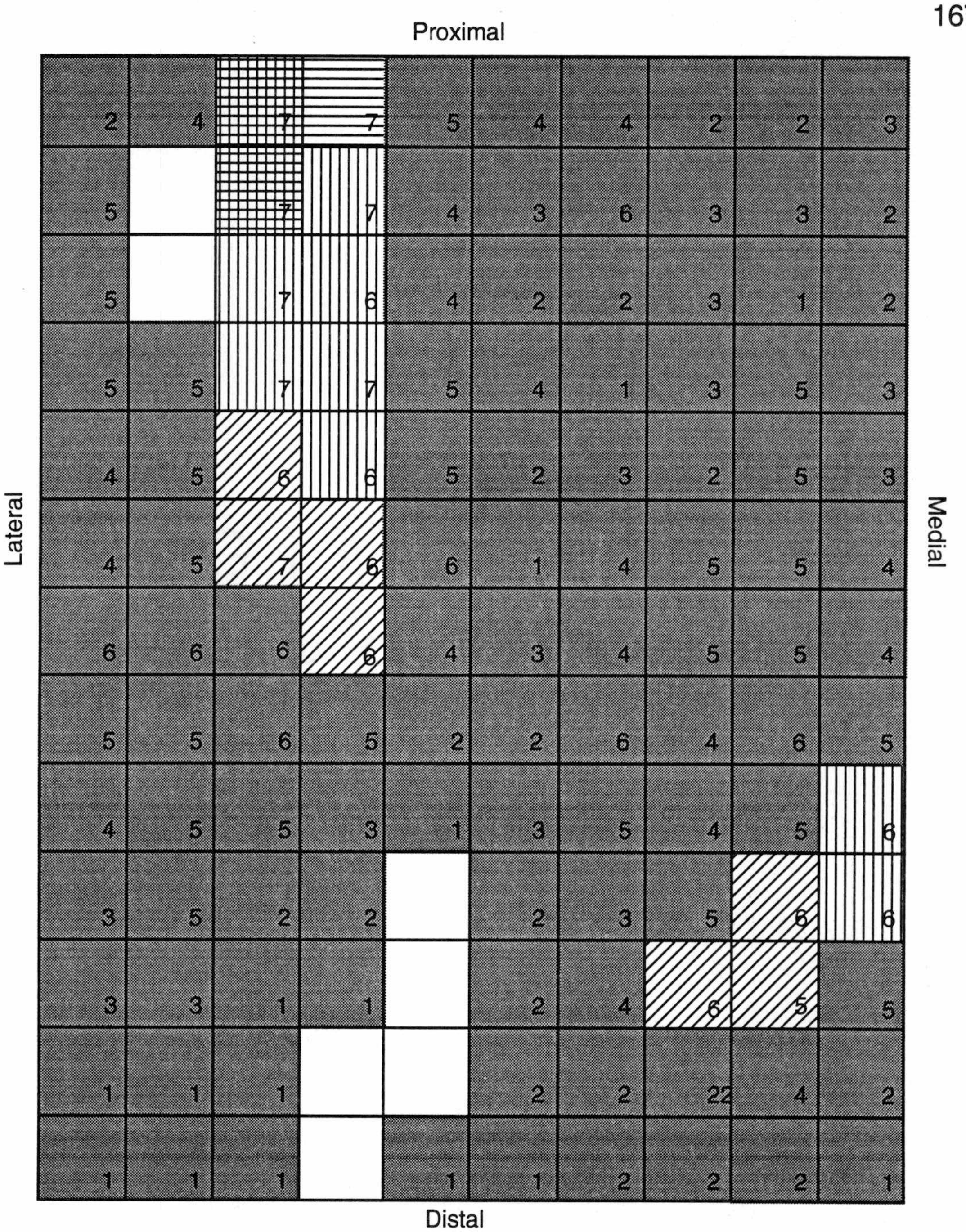


Figure 10-k. Soreness Perception - Quadriceps
100% Group: 48 Hours

LEGEND

- No Soreness
- Mean Soreness Below Threshold
- No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested
- Mean Soreness at 50-58 N
- Mean Soreness at 41-49 N
- Mean Soreness at 32-40 N
- Mean Soreness at 23-31 N

Proximal

Lateral / Medial

1	1	4	4	2	1	1	1	1	1
3	3	5	6	2		1	1		1
2	2	4	5	1	1	2	1	1	1
2	1	4	5	3	1	1	1	1	1
2	1	3	3	2	2	1	2	2	2
2	1	3	3	2	3	1	1	1	2
2	1	3	3	2	3	1	2	1	2
2	1	3	2	1	1	2	2	1	3
2	1	2	2	1	1	3	2	2	4
2	1	1	1	1		2	1	3	5
2	1	1				1	2	3	2
2		1	1			1	2	1	3
2		1				2	1	1	1

Distal

Figure 10-I. Soreness Perception - Quadriceps
100% Group: 72 Hours

LEGEND

☐ No Soreness

▩ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site out of 10 Persons Tested

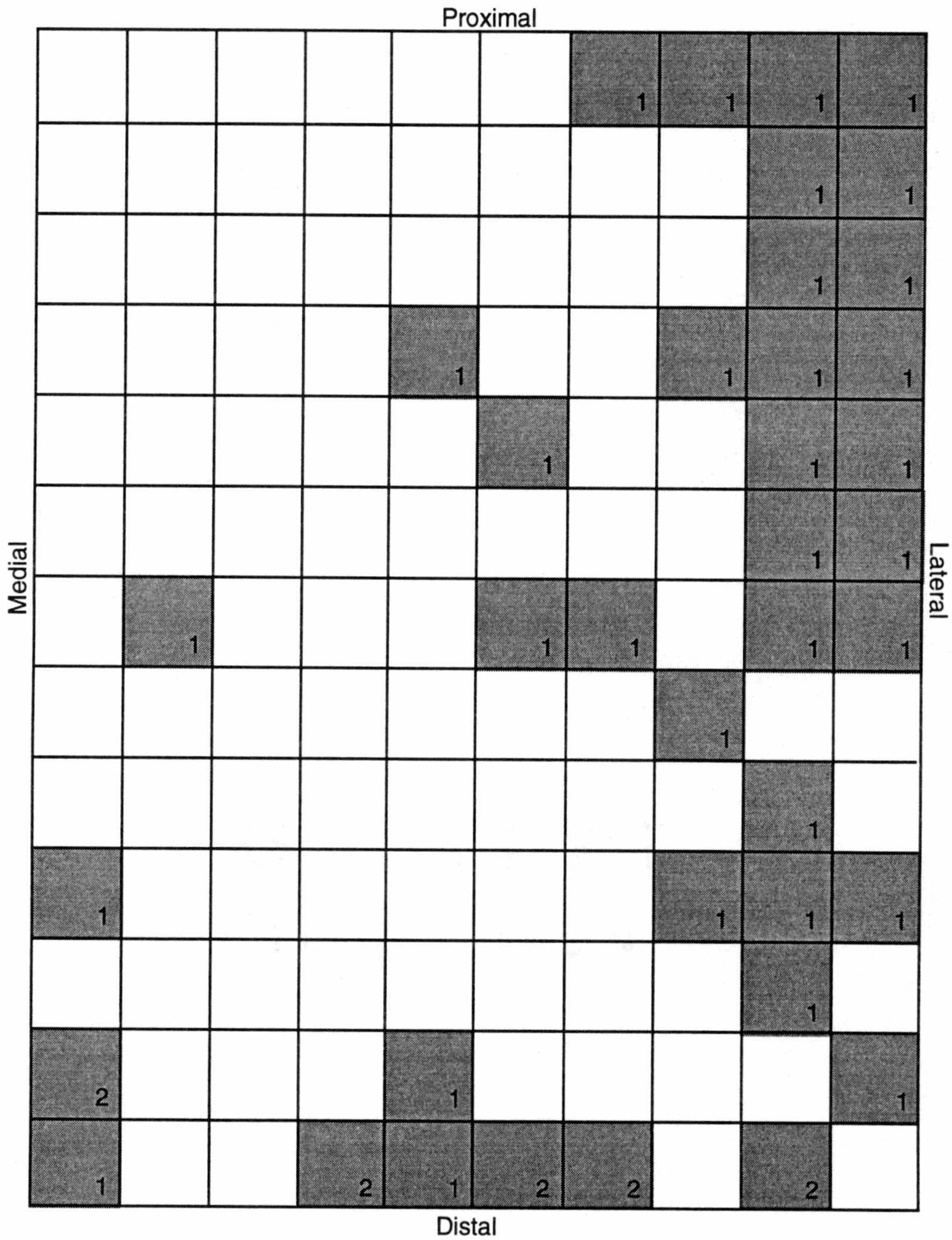


Figure 11-a. Soreness Perception - Hamstrings
60% Group: Pretest

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

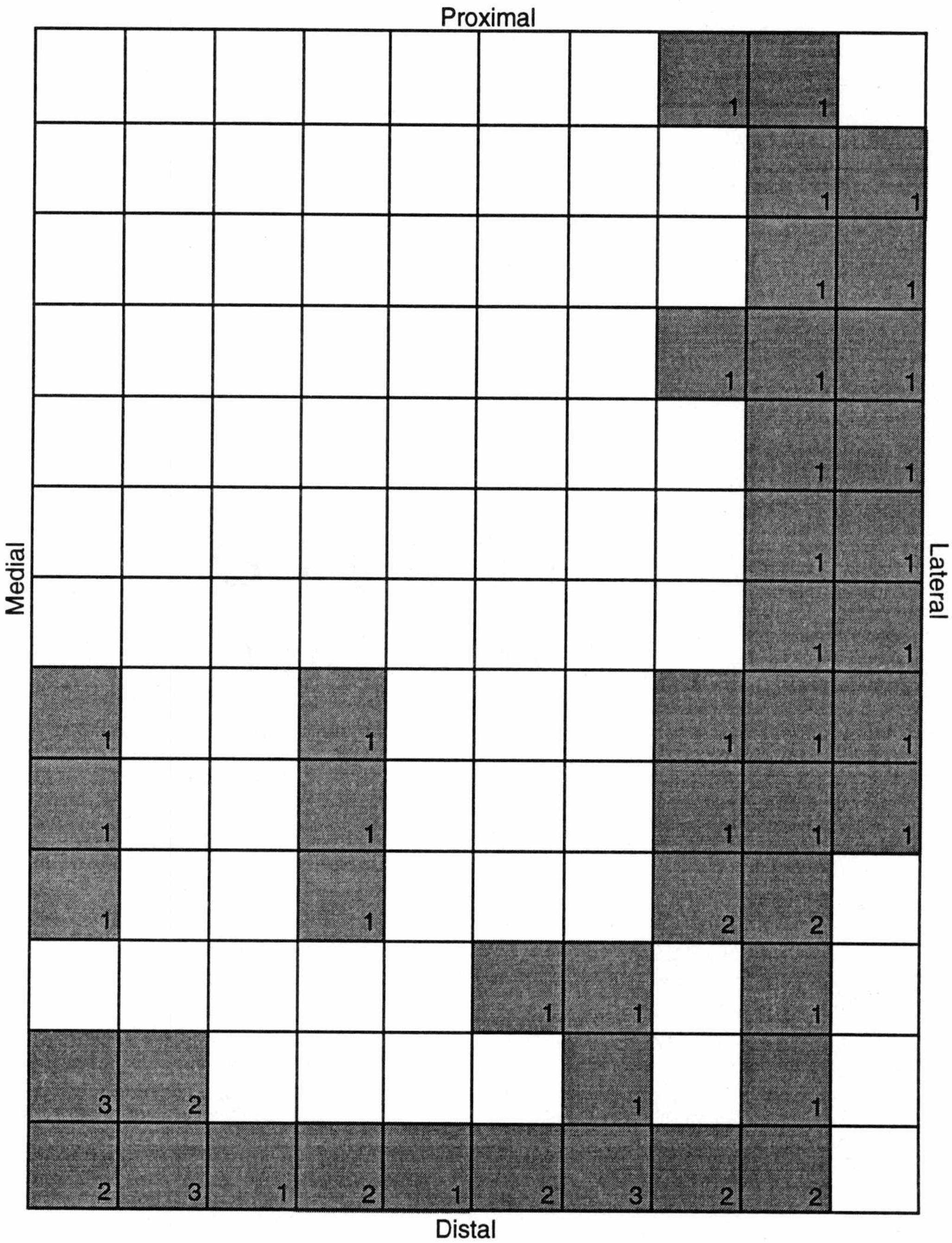


Figure 11-b. Soreness Perception - Hamstrings
60% Group: 24 Hours

LEGEND

- ☐ No Soreness
- ■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

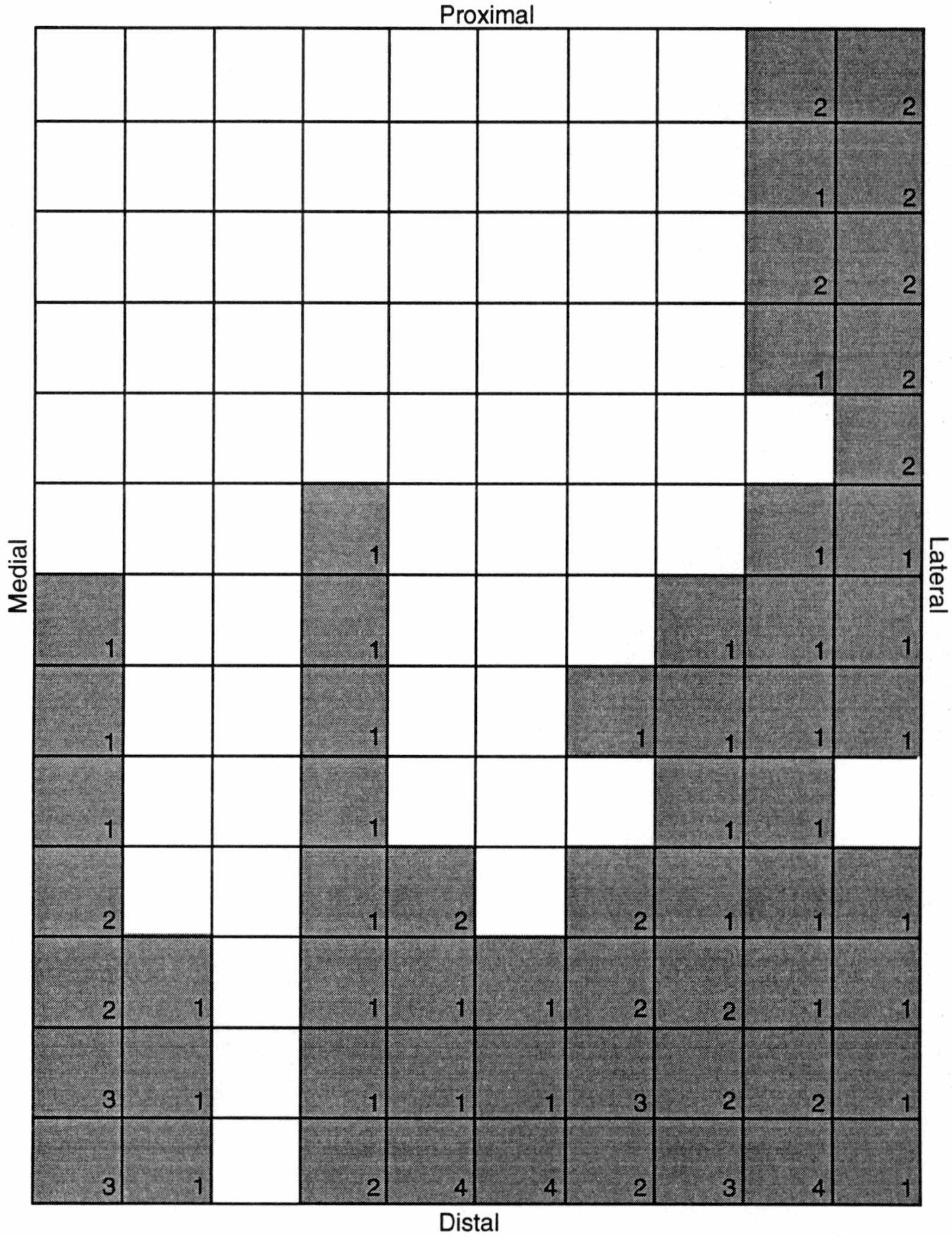


Figure 11-c. Soreness Perception - Hamstrings
60% Group: 48 Hours

LEGEND

- No Soreness
- Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

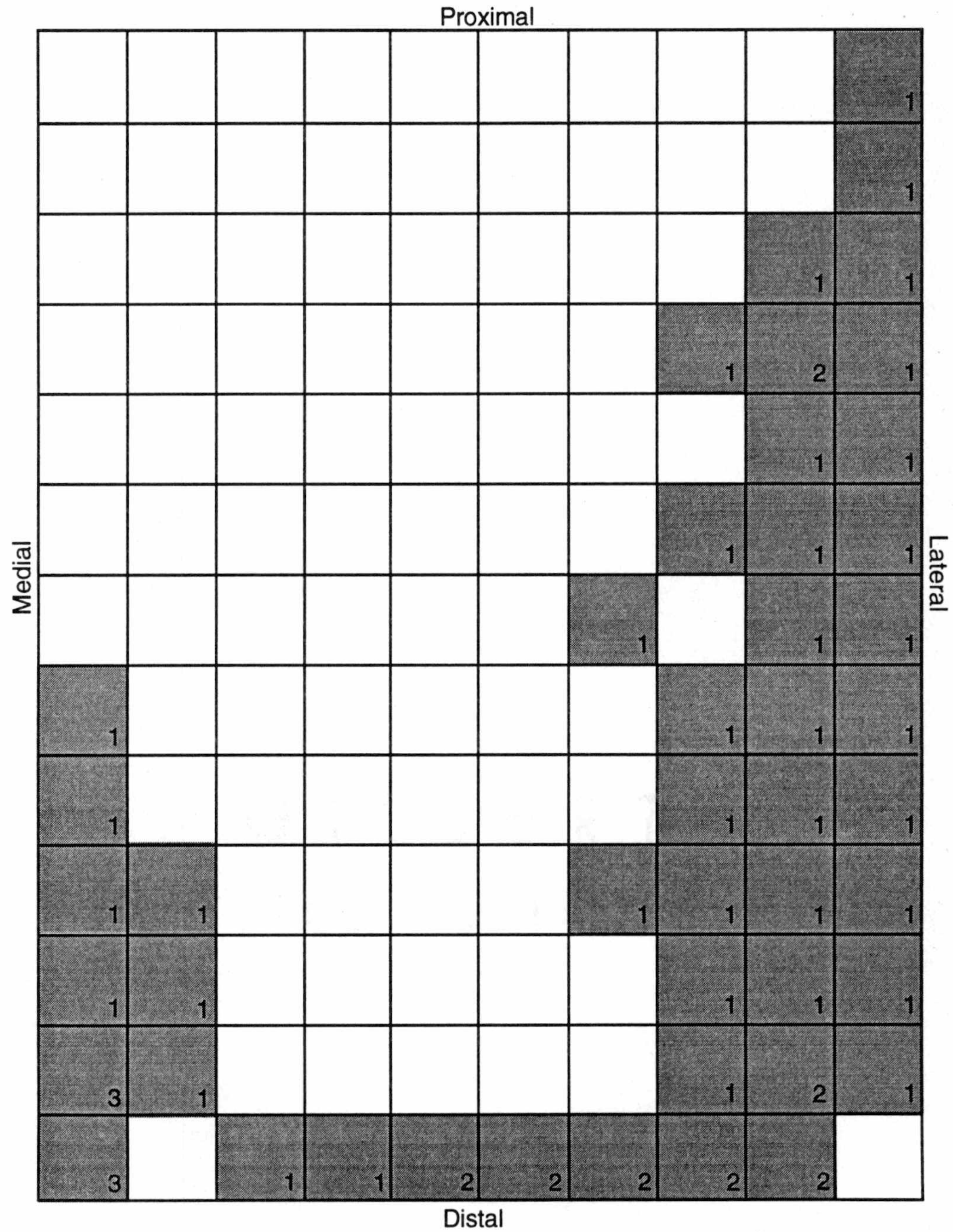


Figure 11-d. Soreness Perception - Hamstrings
60% Group: 72 Hours

LEGEND

- No Soreness
- Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

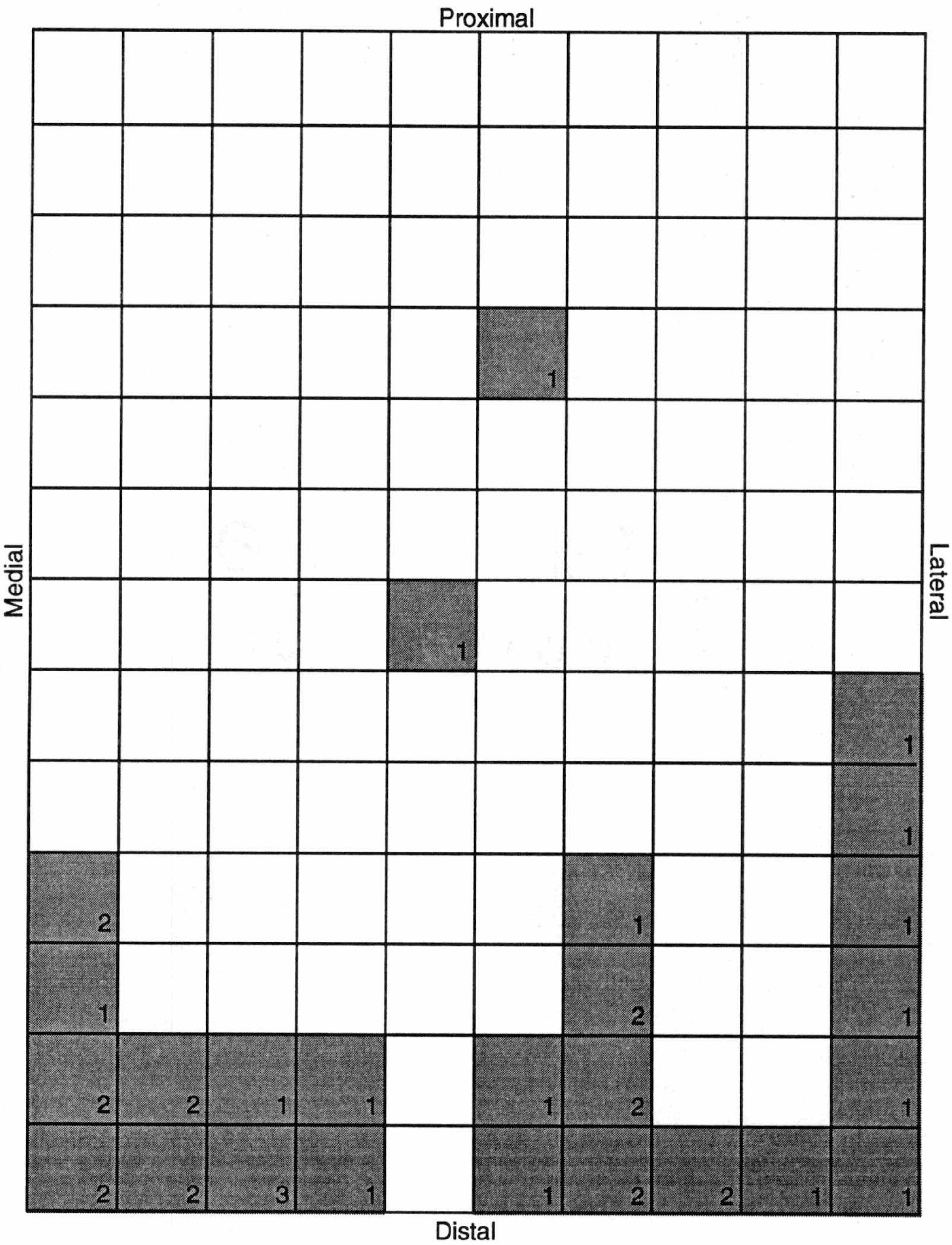


Figure 11-e. Soreness Perception - Hamstrings
80% Group: Pretest

LEGEND

☐ No Soreness

■ Mean Soreness
Below Threshold

No (1, 2 . . .) = Total Persons with
Soreness Per Site Out of 10
Persons Tested

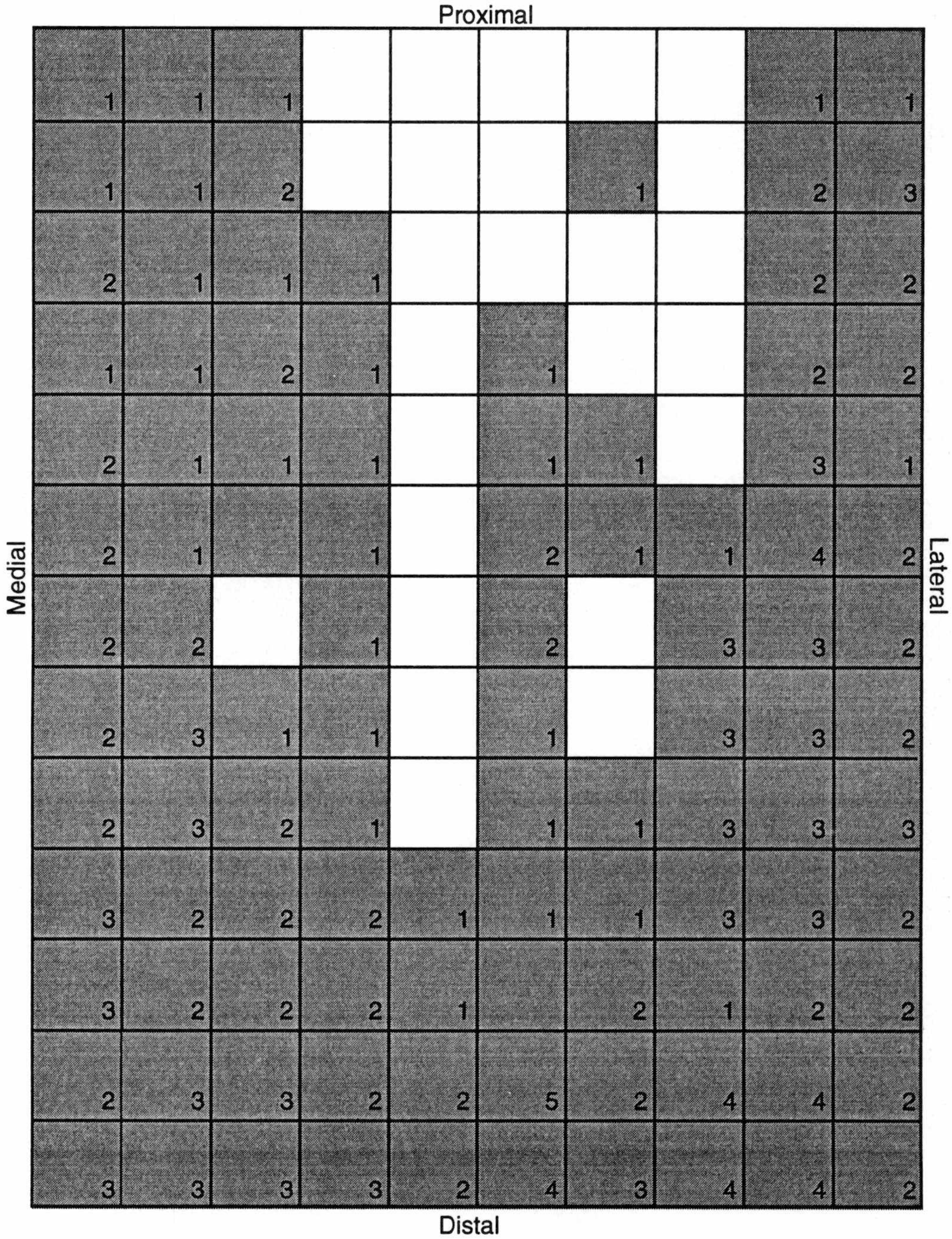


Figure 11-f. Soreness Perception - Hamstrings
80% Group: 24 Hours

LEGEND

- ☐ No Soreness
- ■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

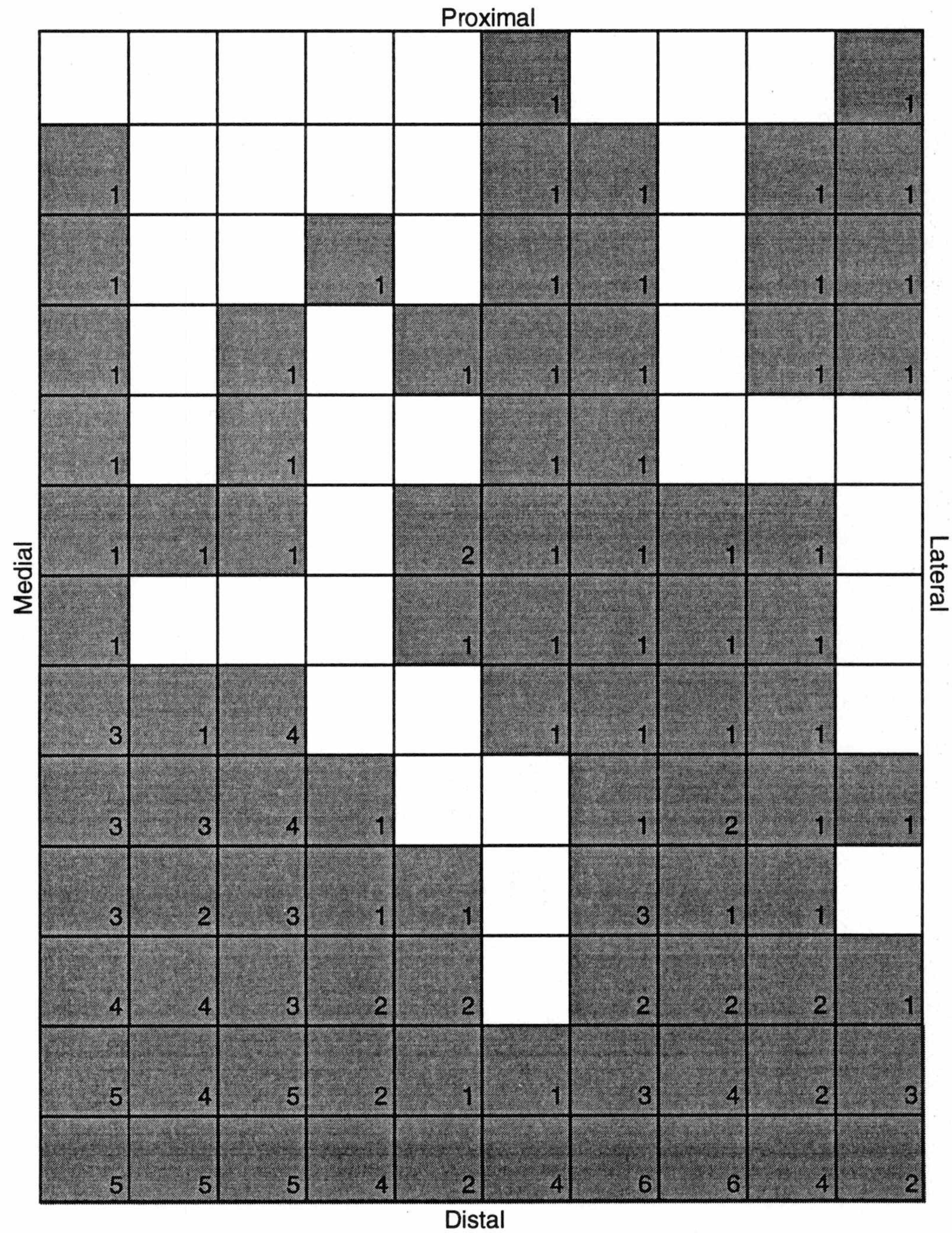


Figure 11-g. Soreness Perception - Hamstrings
80% Group: 48 Hours

LEGEND

- ☐ No Soreness
- ■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

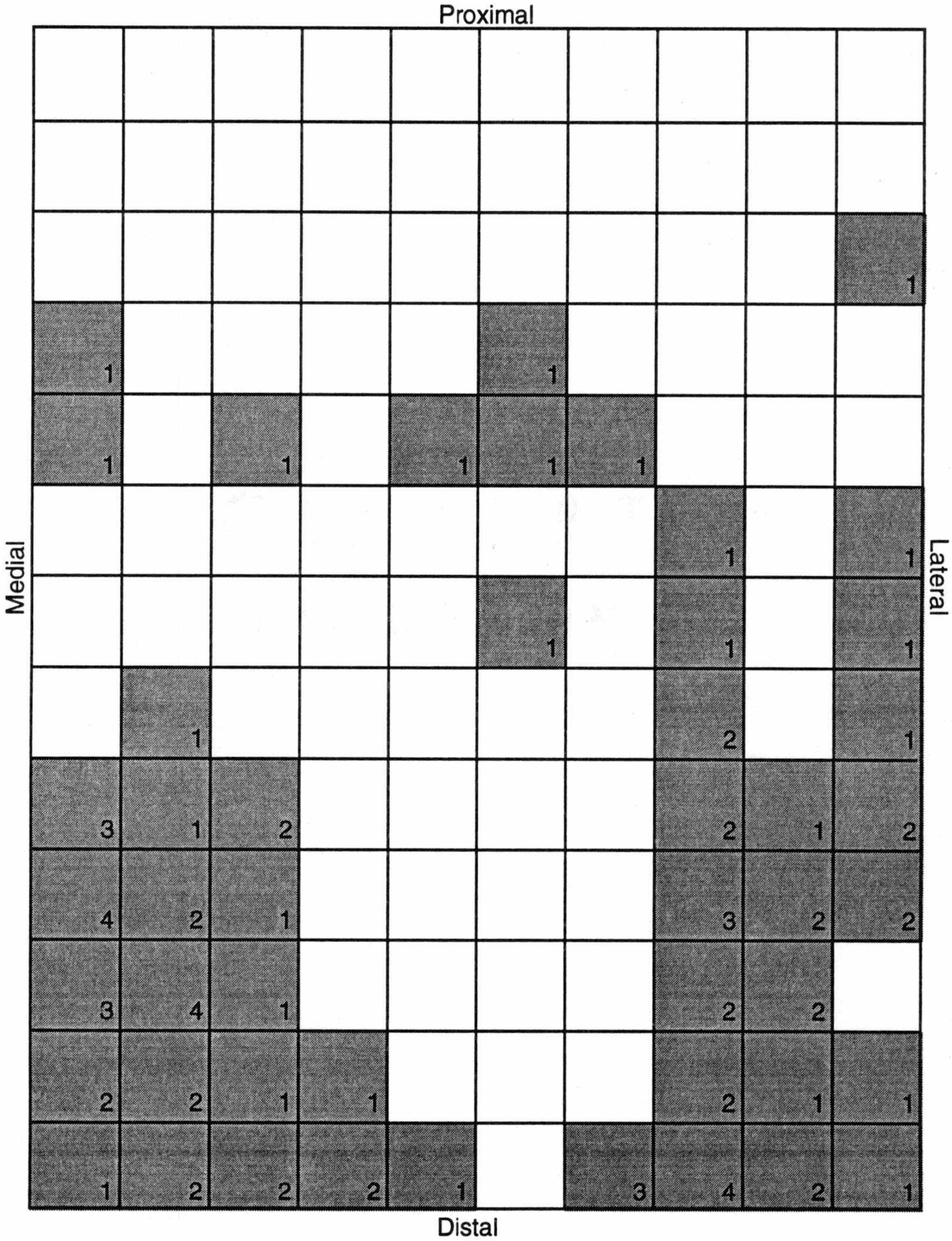


Figure 11-h. Soreness Perception - Hamstrings
80% Group: 72 Hours

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

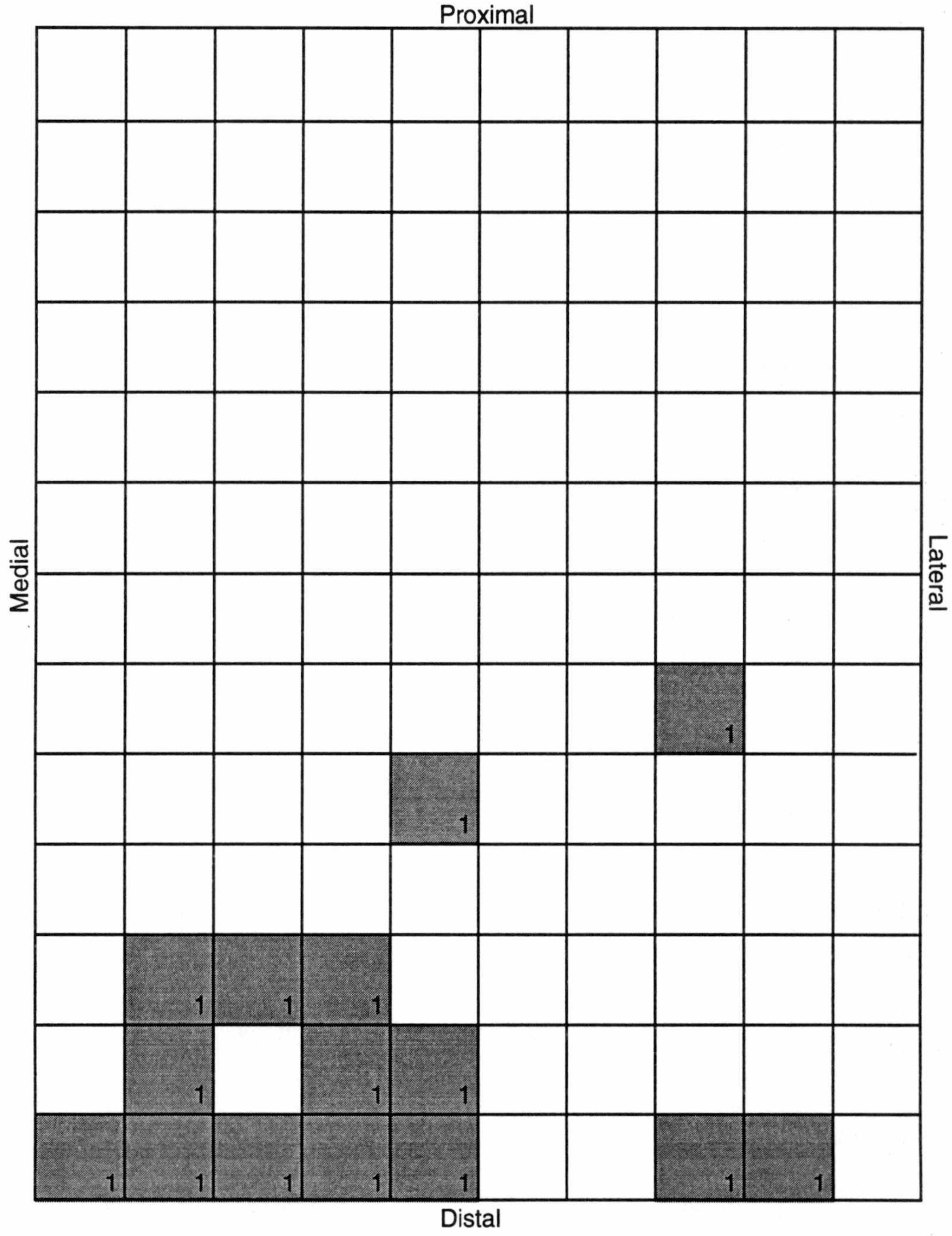


Figure 11-i. Soreness Perception - Hamstrings
100% Group: Pretest

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

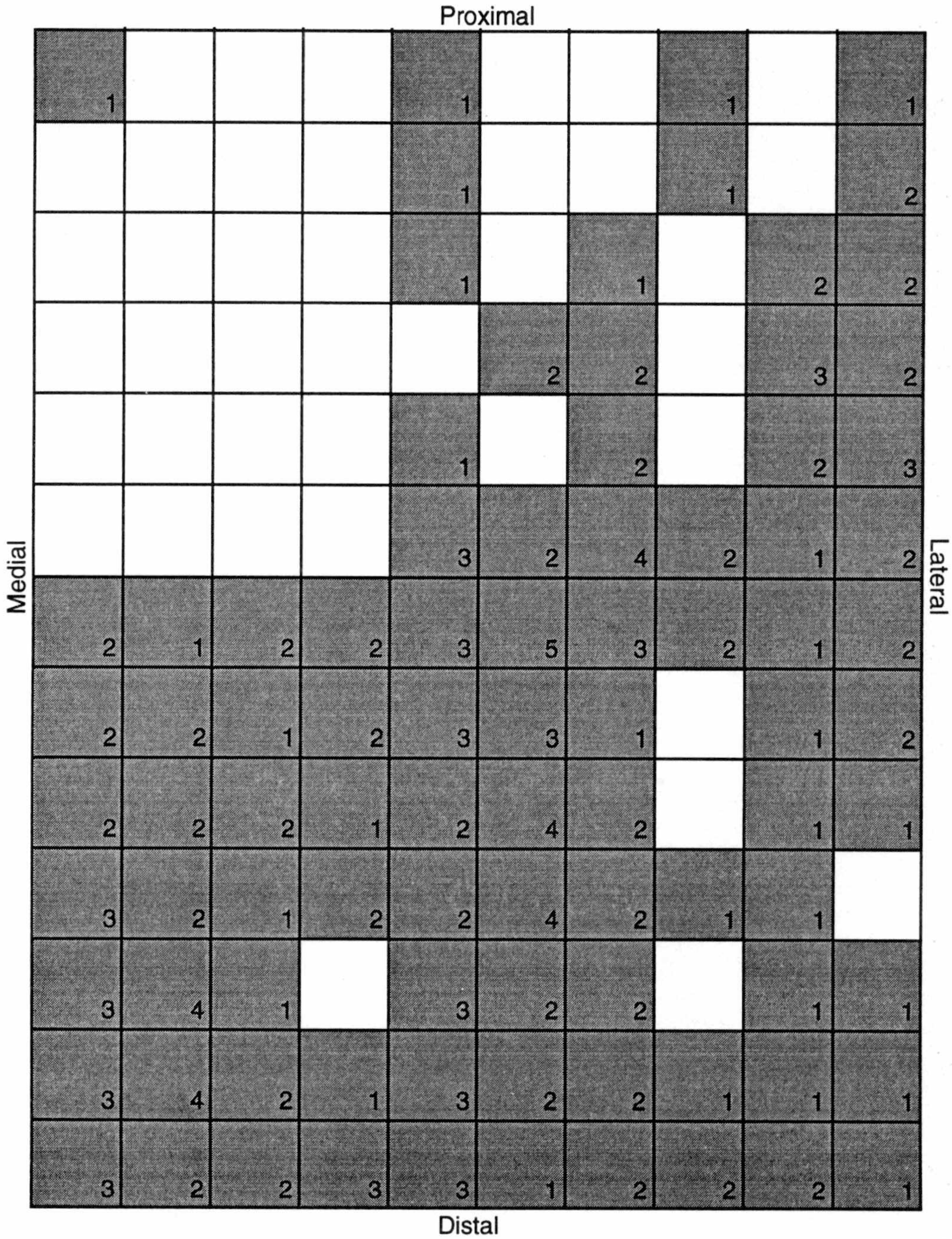


Figure 11-j. Soreness Perception - Hamstrings
100% Group: 24 Hours Post

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

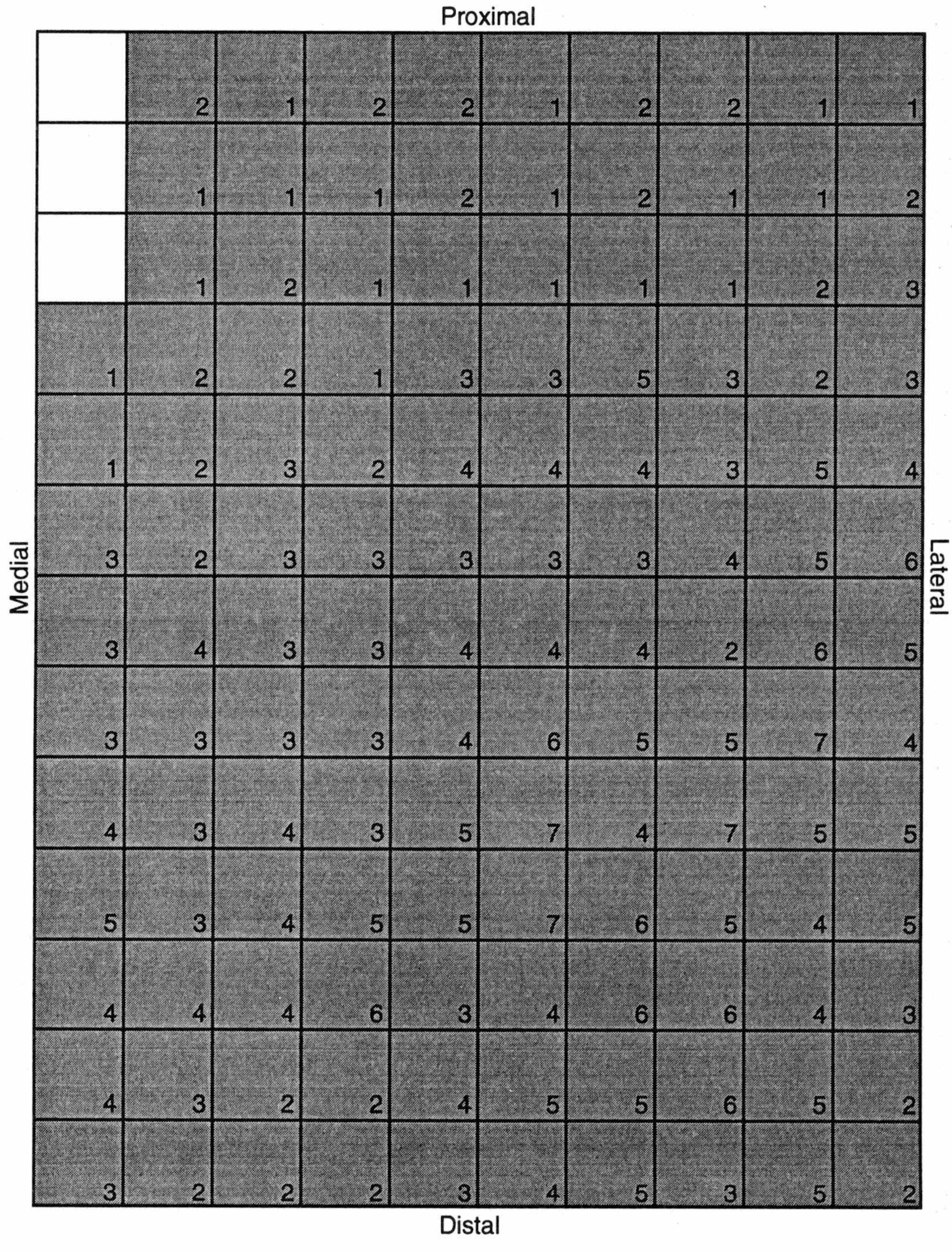


Figure 11-k. Soreness Perception - Hamstrings
100% Group: 48 Hours

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

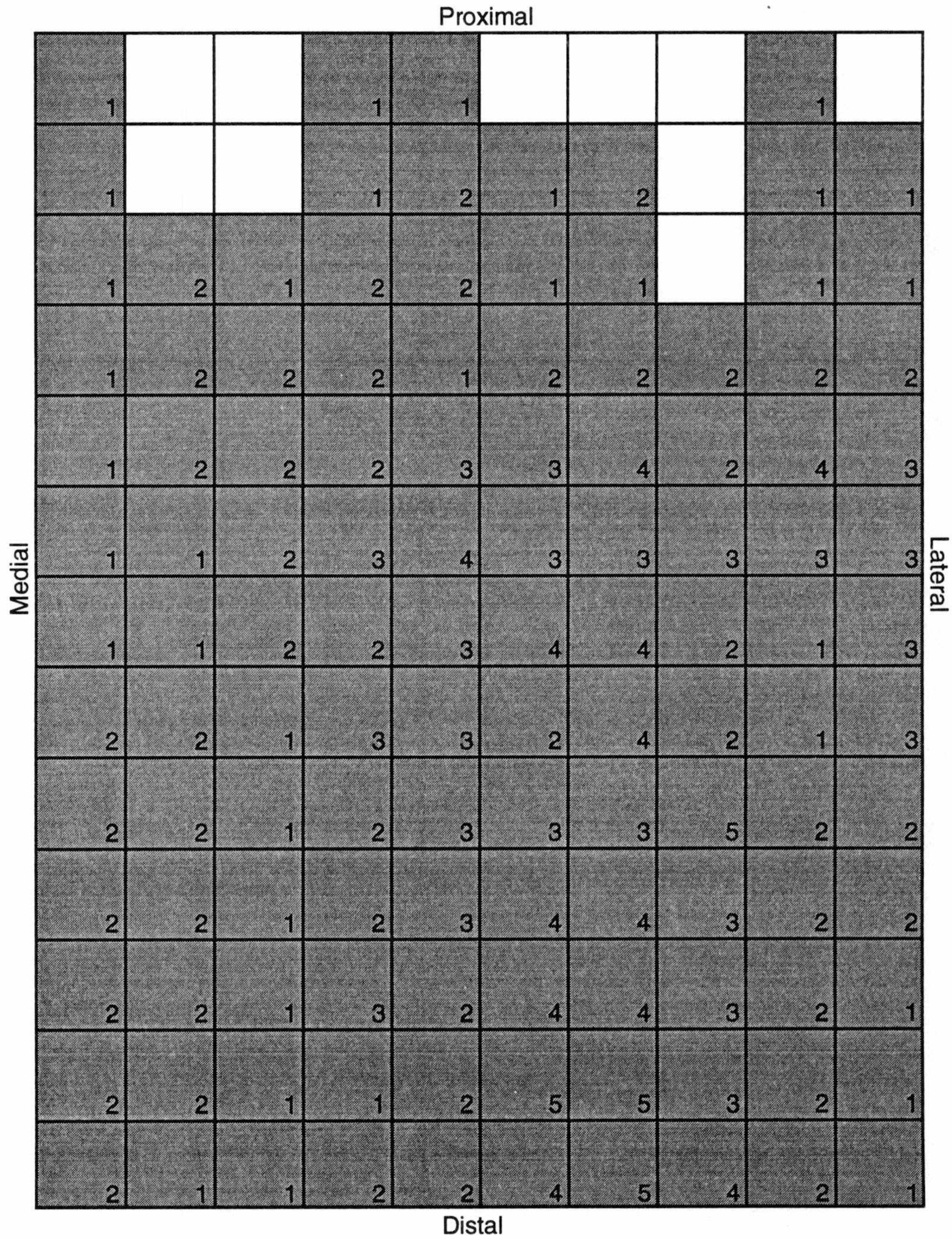


Figure 11-I. Soreness Perception - Hamstrings
100% Group: 72 Hours

LEGEND

☐ No Soreness

■ Mean Soreness Below Threshold

No (1, 2 . . .) = Total Persons with Soreness Per Site Out of 10 Persons Tested

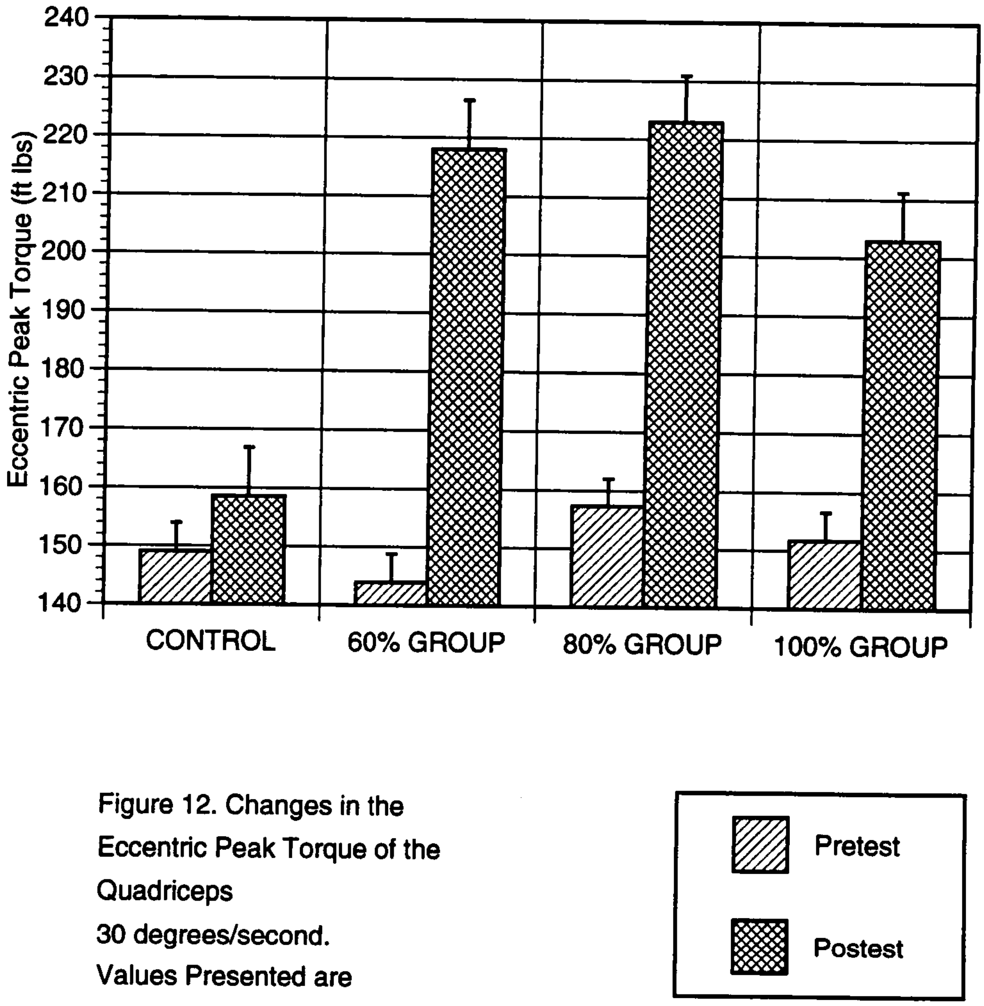


Figure 12. Changes in the Eccentric Peak Torque of the Quadriceps
30 degrees/second.
Values Presented are Adjusted Means + SE.

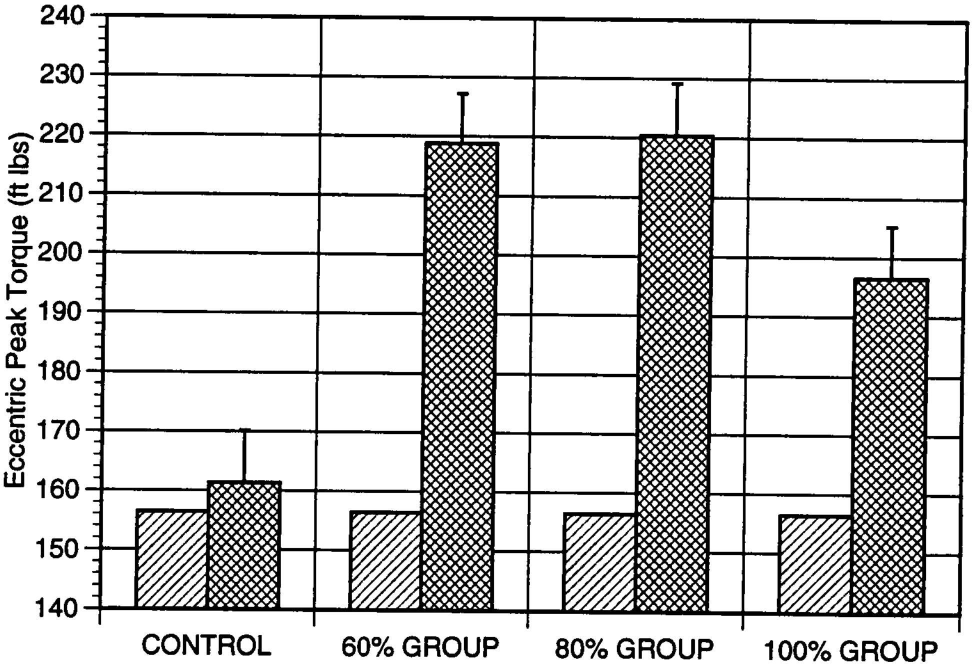
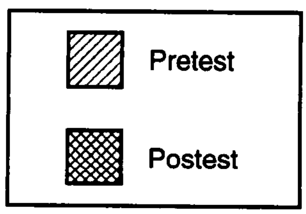


Figure 13. Changes in the
Eccentric Peak Torque of the
Quadriceps
60 degrees/second.
Values Presented are
Adjusted Means + SE.



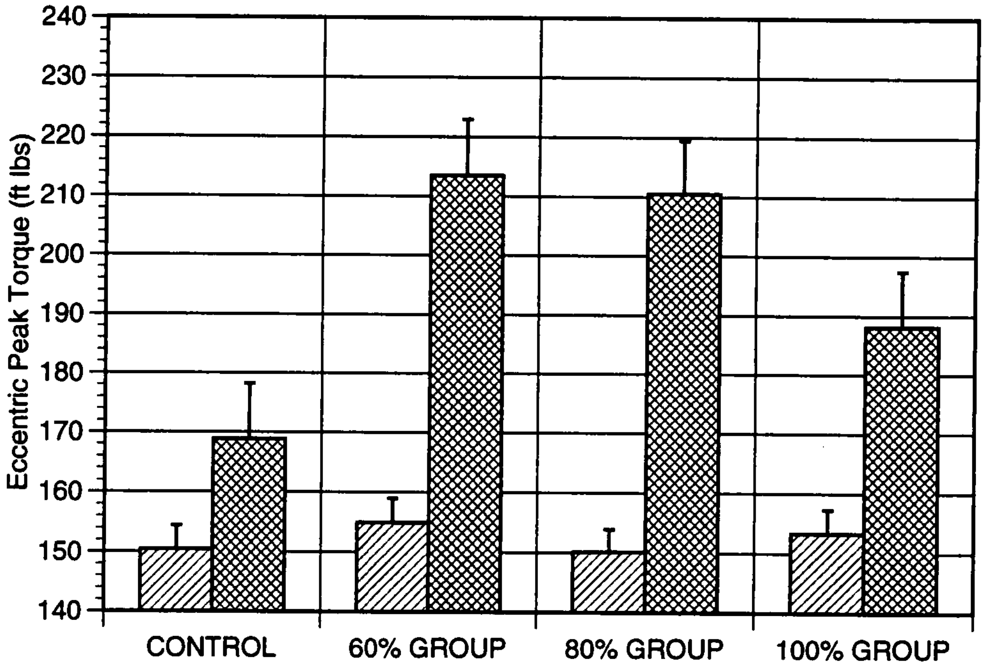
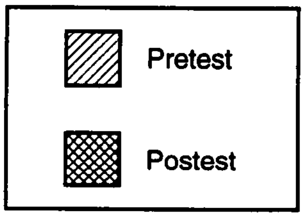


Figure 14. Changes in the
Eccentric Peak Torque of the
Quadriceps
90 degrees/second.
Values Presented are
Adjusted Means + SE.



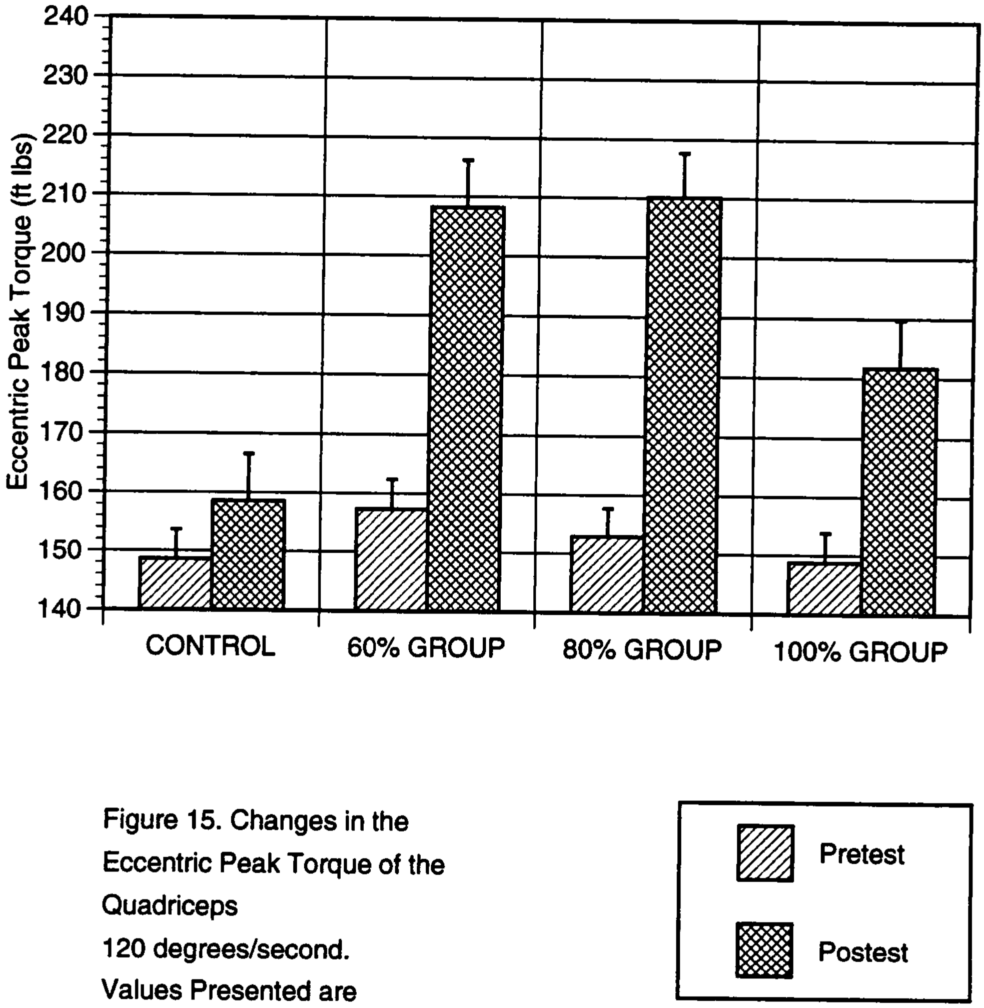


Figure 15. Changes in the Eccentric Peak Torque of the Quadriceps
120 degrees/second.
Values Presented are Adjusted Means + SE.

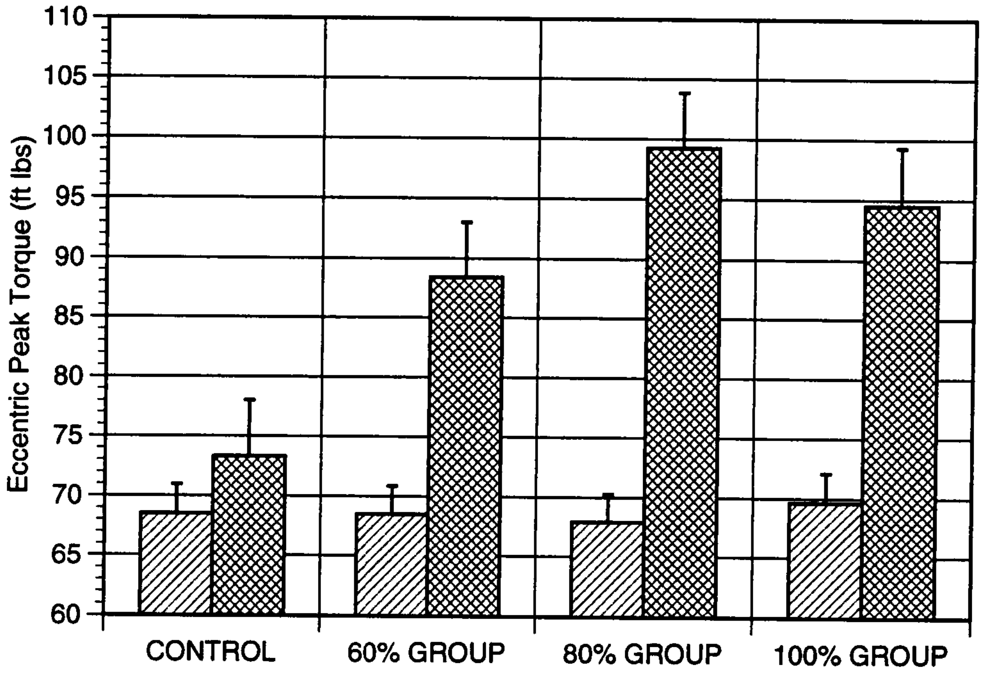
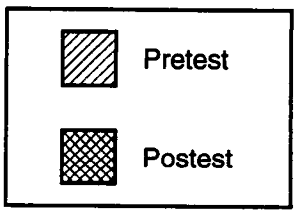


Figure 16. Changes in the Eccentric Peak Torque of the Hamstrings
30 degrees/second.
Values Presented are Adjusted Means + SE.



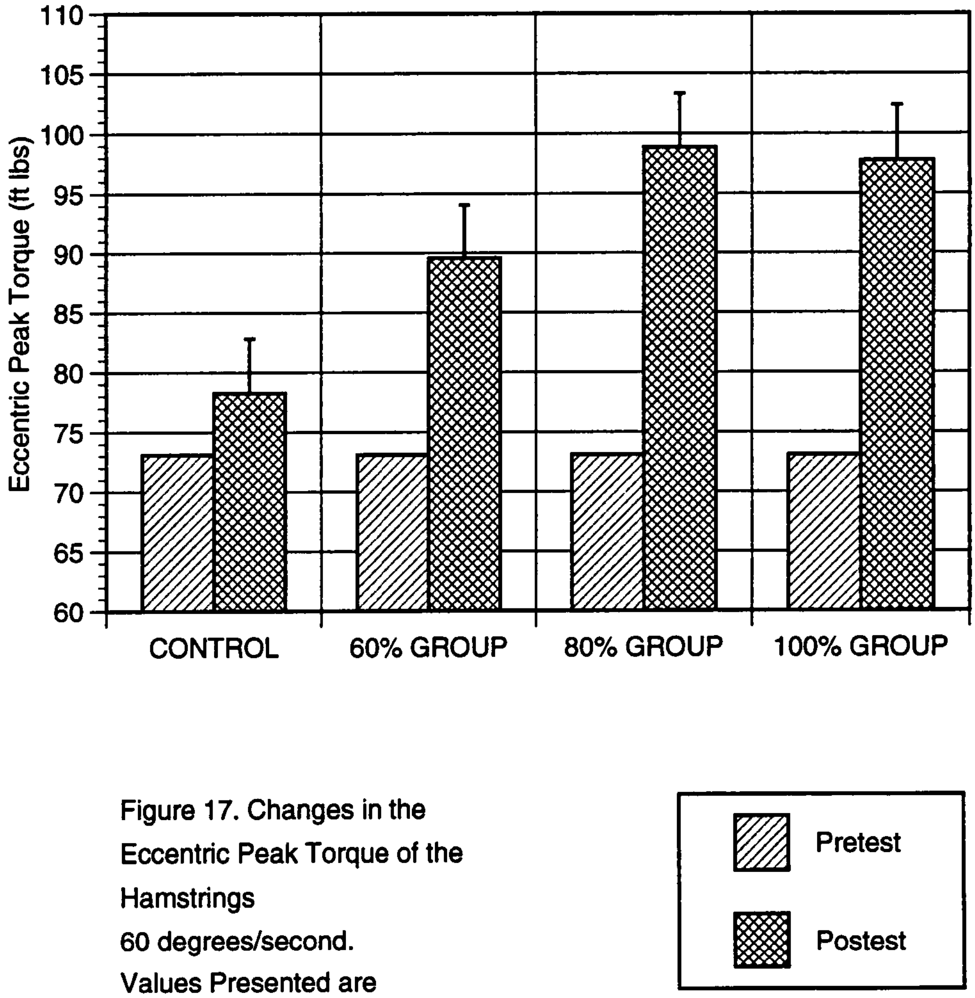


Figure 17. Changes in the Eccentric Peak Torque of the Hamstrings
60 degrees/second.
Values Presented are Adjusted Means + SE.

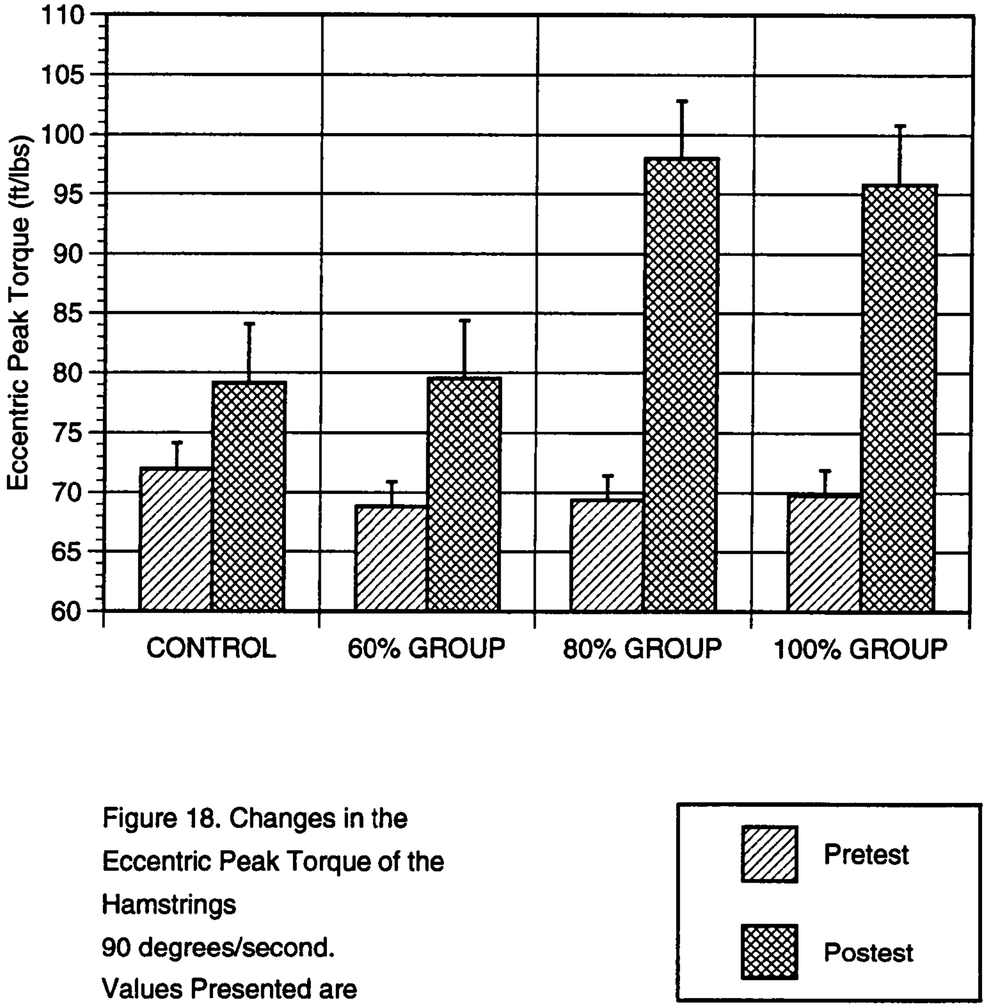


Figure 18. Changes in the Eccentric Peak Torque of the Hamstrings
90 degrees/second.
Values Presented are Adjusted Means.

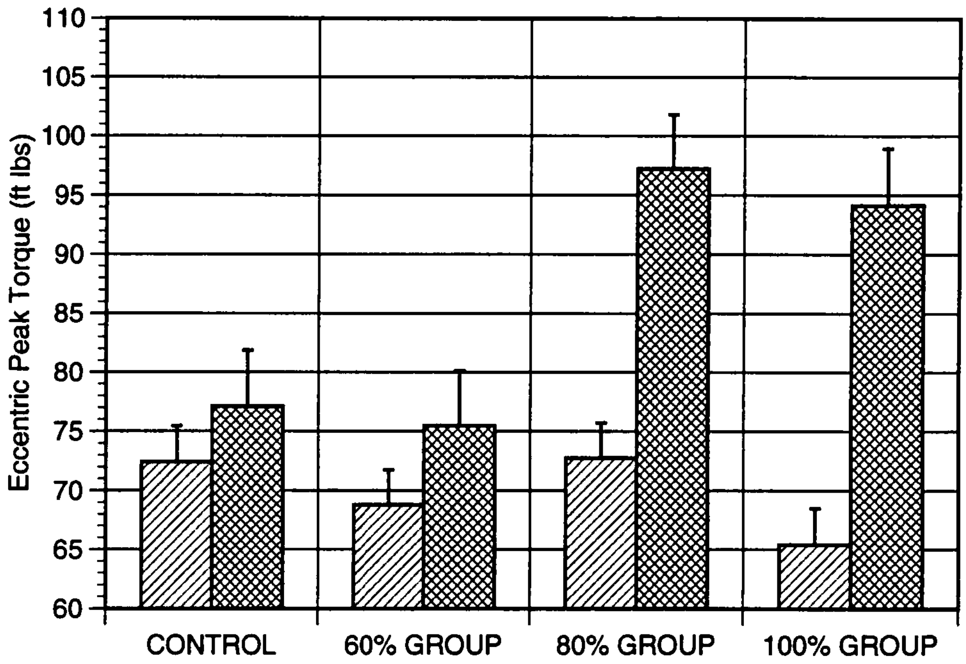


Figure 19. Changes in the Eccentric Peak Torque of the Hamstrings
120 degrees/second.
Values Presented are Adjusted Means + SE.

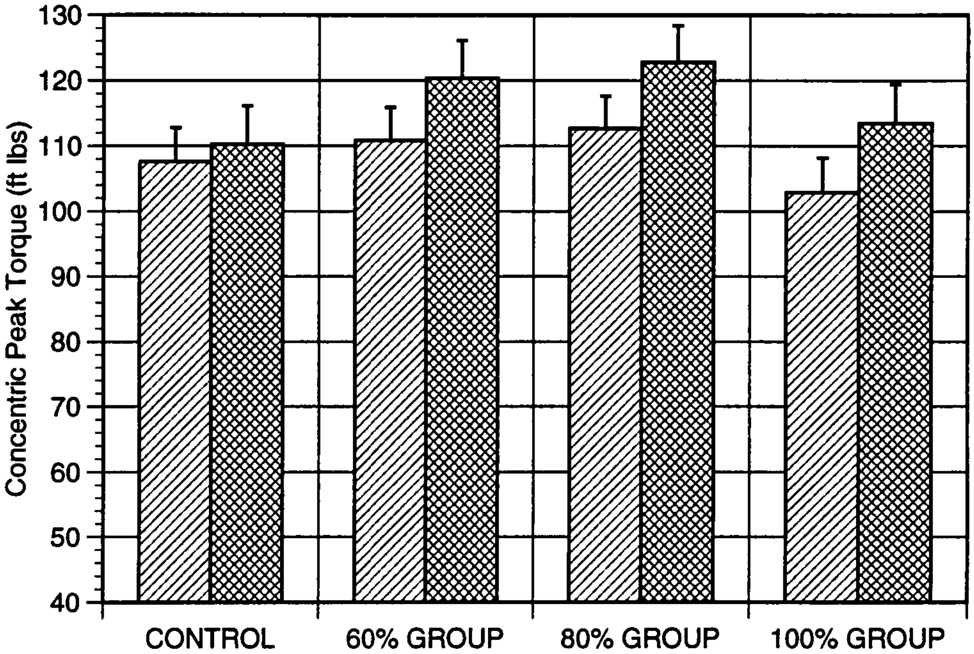


Figure 20. Changes in the Concentric Peak Torque of the Quadriceps
60 degrees/second.
Values Presented are Adjusted Means + SE.

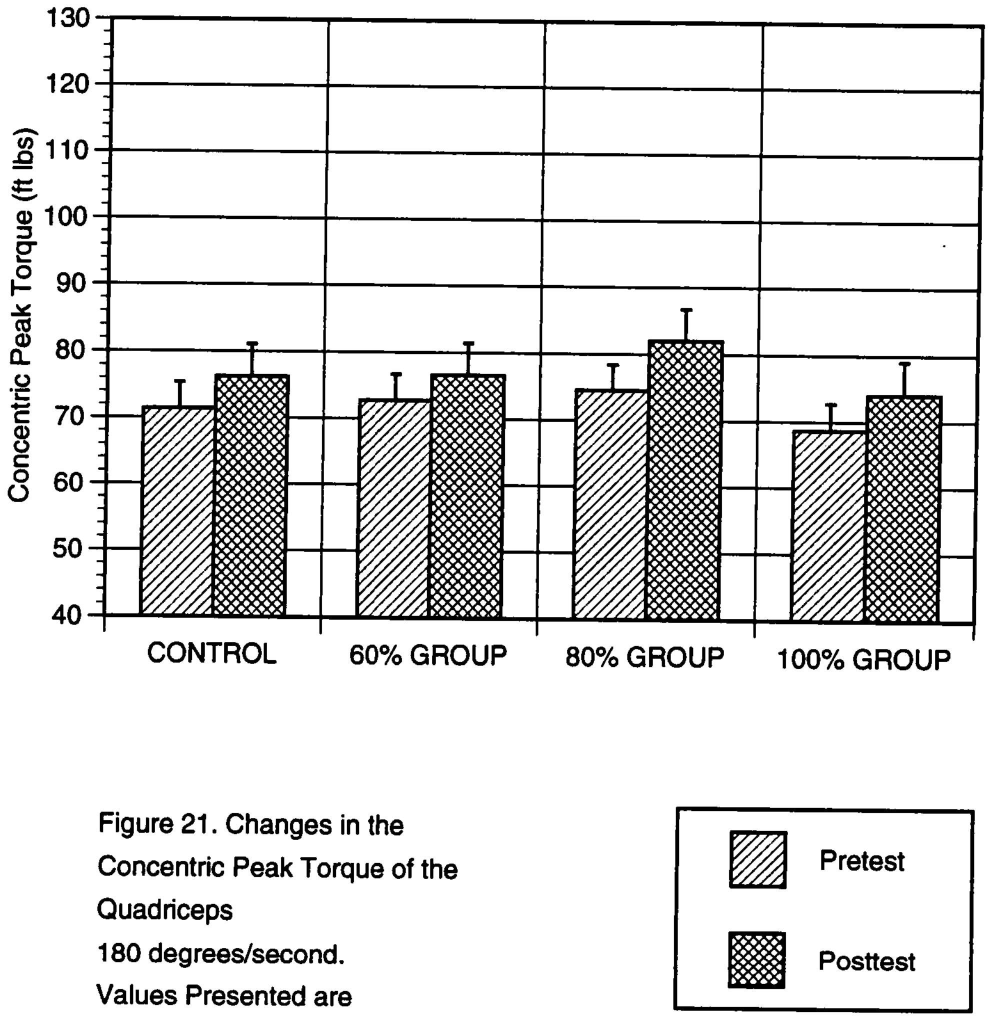


Figure 21. Changes in the Concentric Peak Torque of the Quadriceps 180 degrees/second. Values Presented are Adjusted Means + SE.

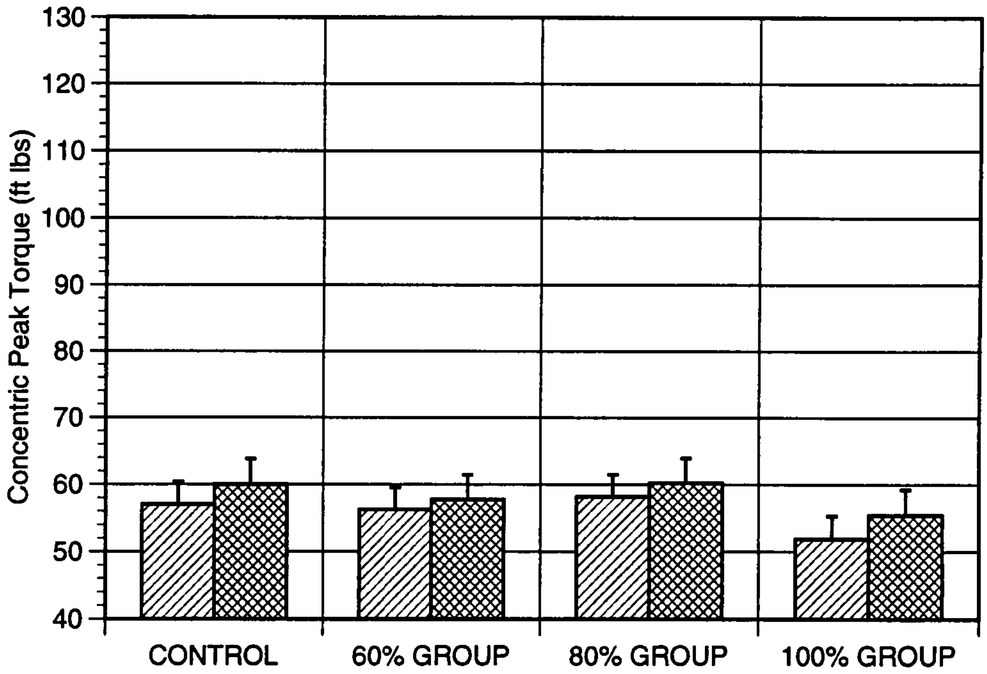


Figure 22. Changes in the
Concentric Peak Torque of the
Quadriceps
300 degrees/second.
Values Presented are
Adjusted Means + SE.

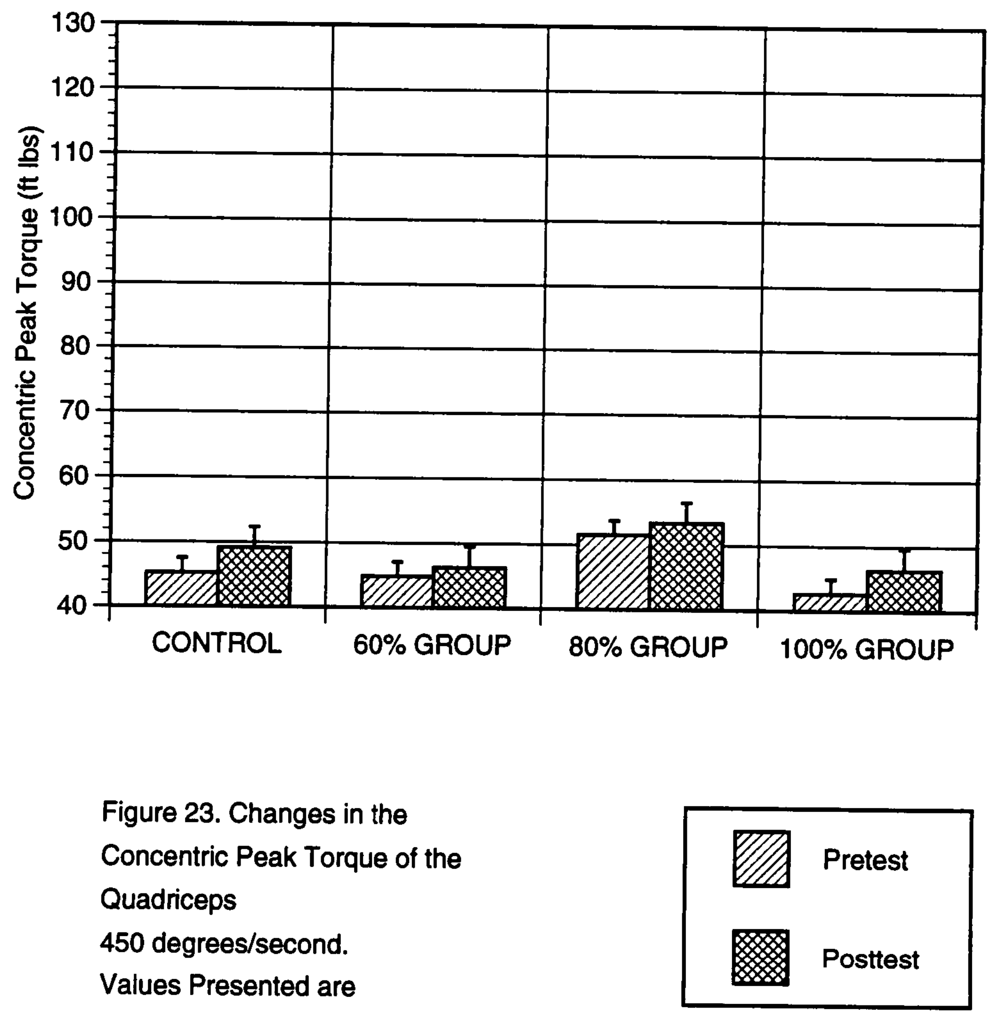


Figure 23. Changes in the Concentric Peak Torque of the Quadriceps 450 degrees/second. Values Presented are Adjusted Means + SE.

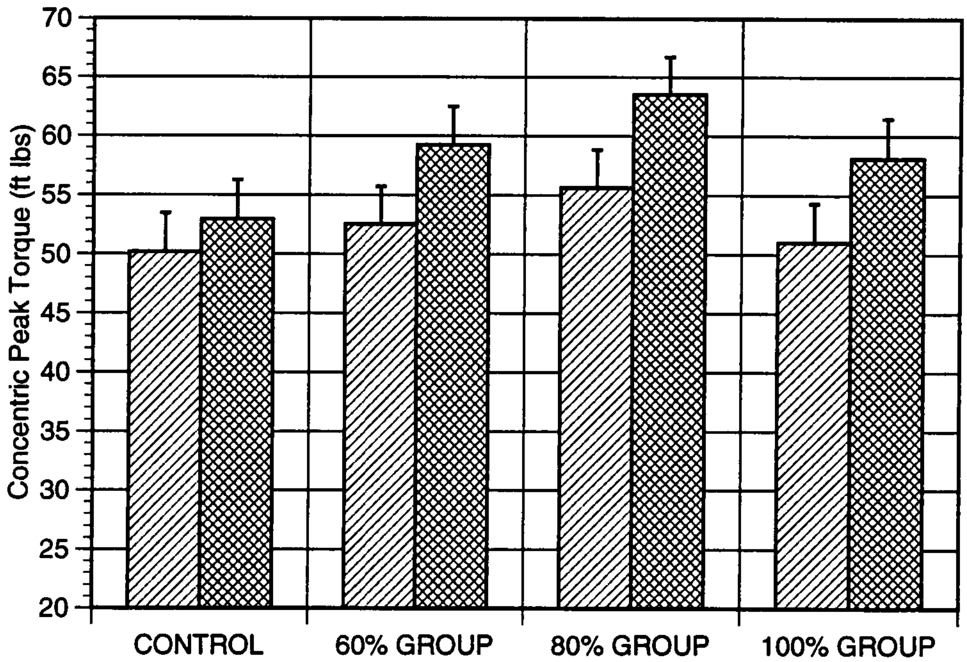
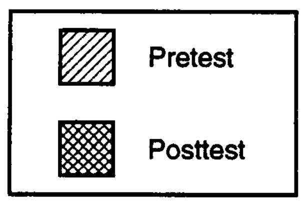


Figure 24. Changes in the Concentric Peak Torque of the Hamstrings
60 degrees/second.
Values Presented are Adjusted Means + SE.



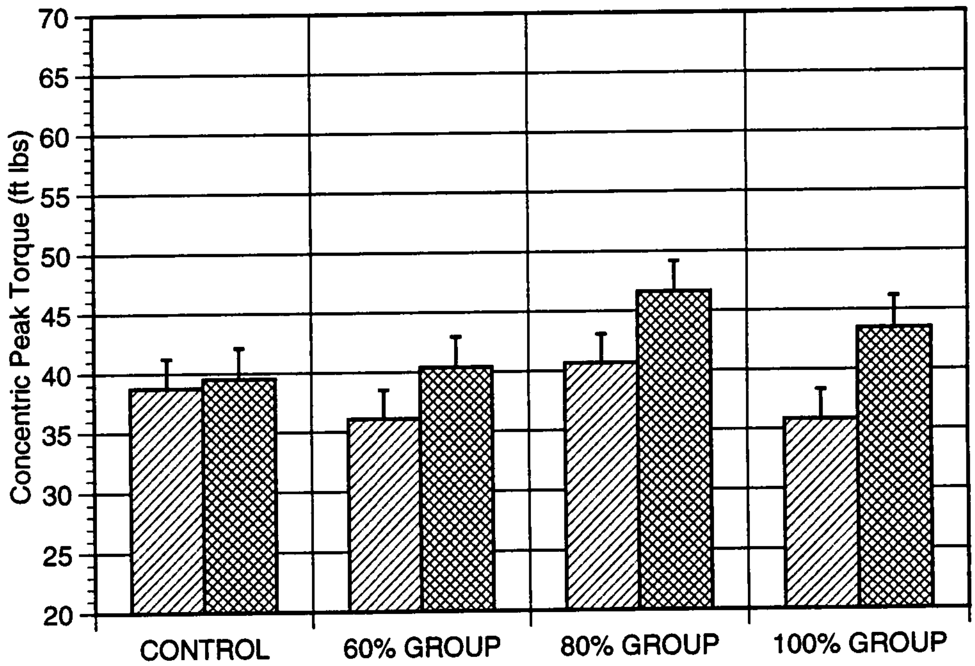
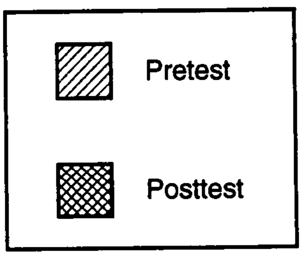


Figure 25. Changes in the Concentric Peak Torque of the Hamstrings
180 degrees/second.
Values Presented are Adjusted Means + SE.



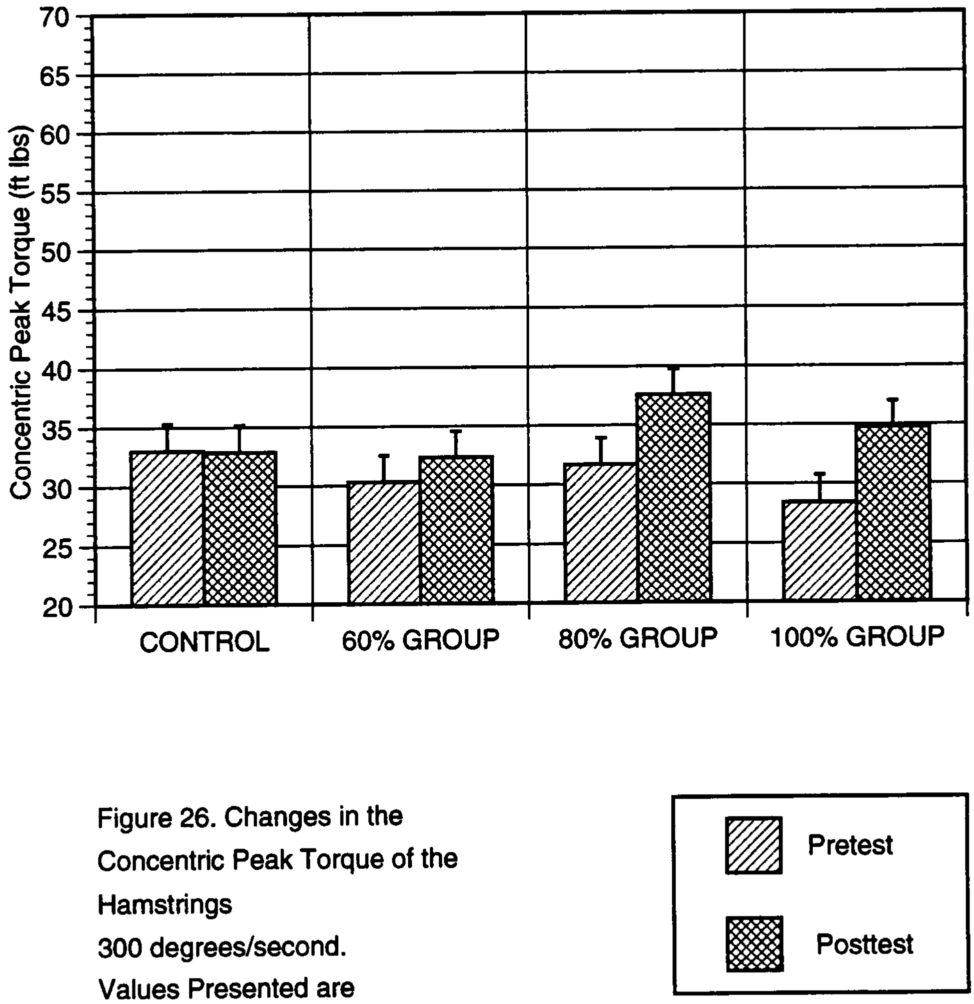


Figure 26. Changes in the Concentric Peak Torque of the Hamstrings
300 degrees/second.
Values Presented are Adjusted Means + SE.

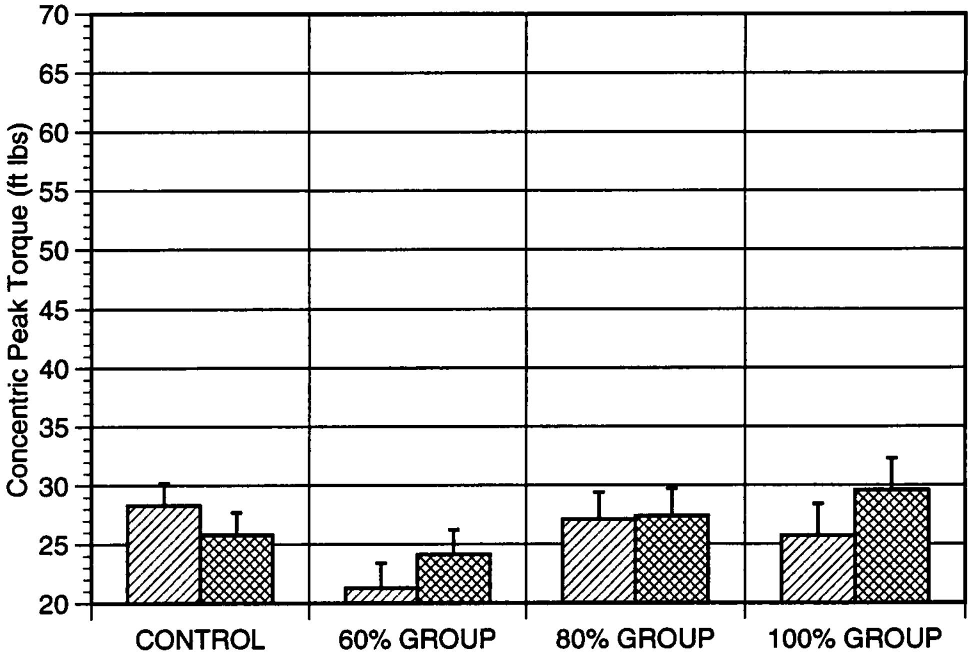
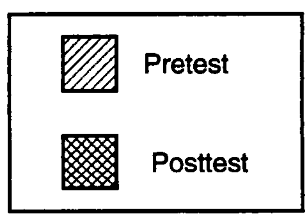


Figure 27. Changes in the Concentric Peak Torque of the Hamstrings
450 degrees/second.
Values Presented are Adjusted Means + SE.



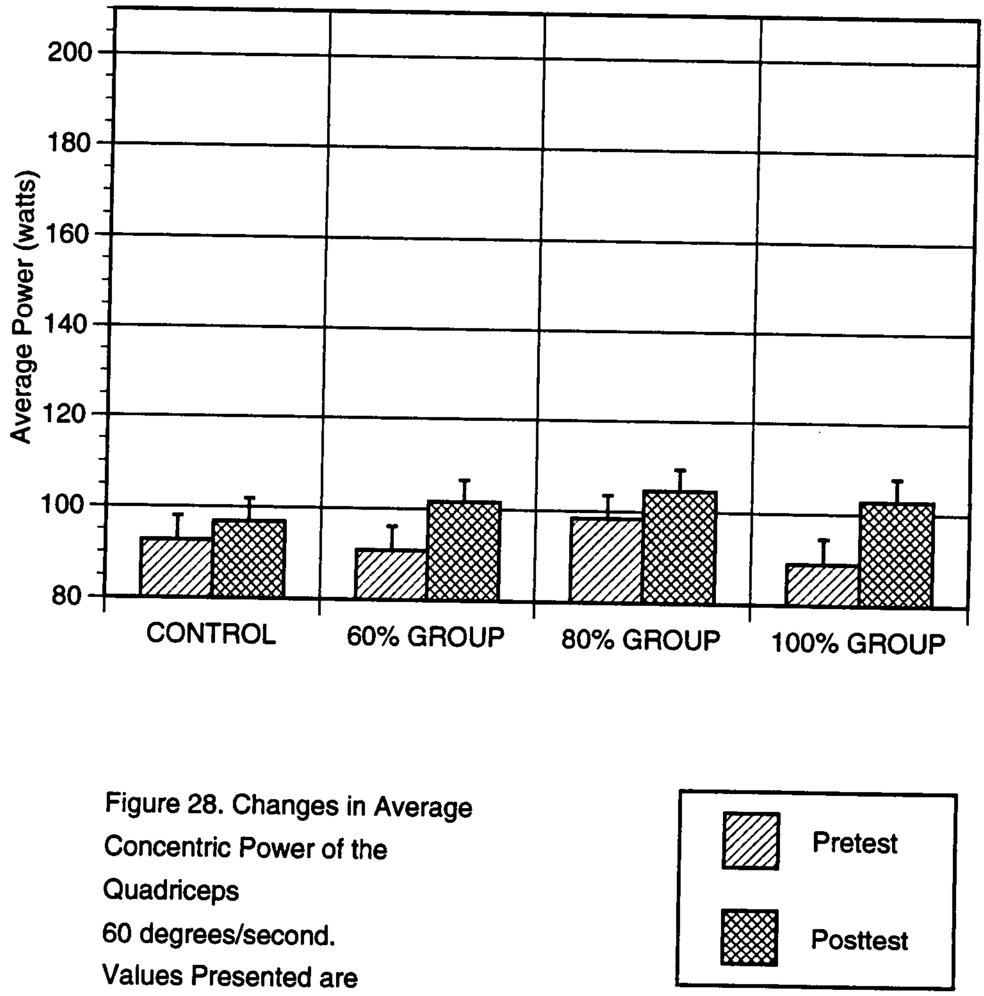


Figure 28. Changes in Average
Concentric Power of the
Quadriceps
60 degrees/second.
Values Presented are
adjusted Means + SE.

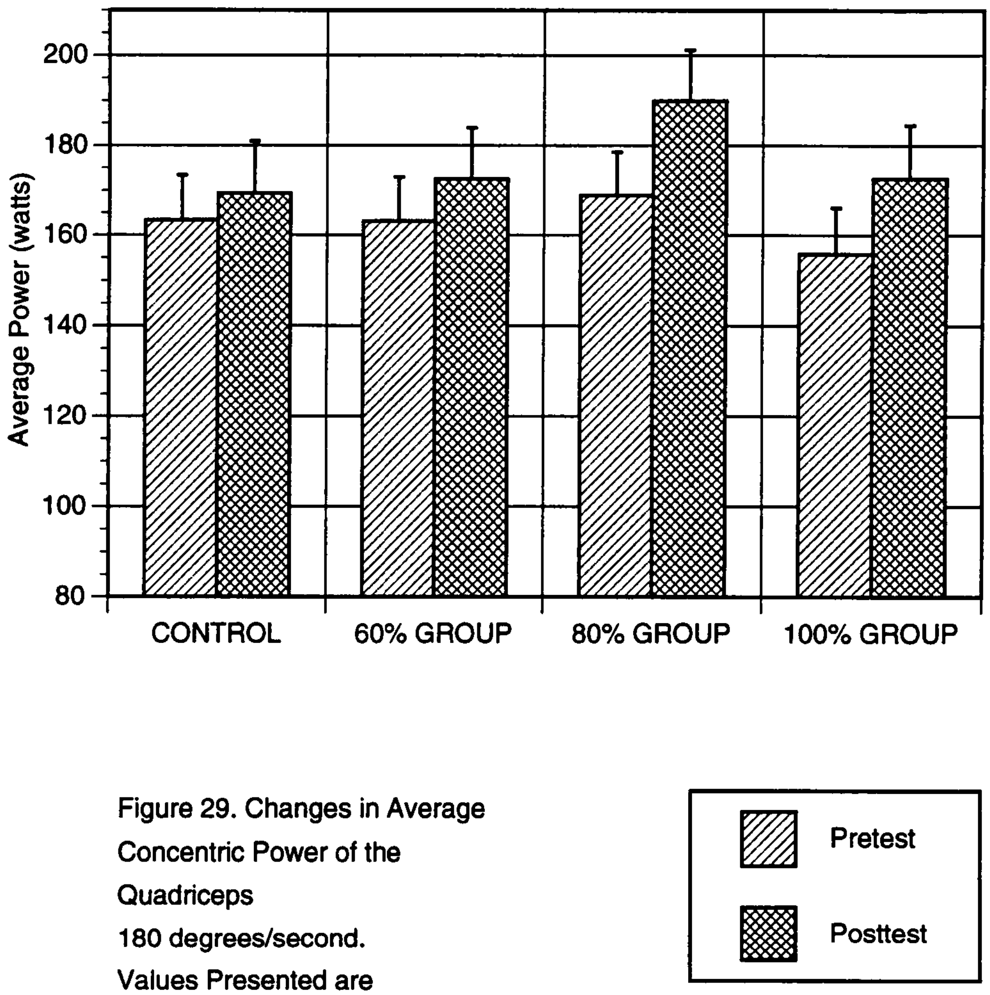


Figure 29. Changes in Average Concentric Power of the Quadriceps
180 degrees/second.
Values Presented are Adjusted Means + SE.

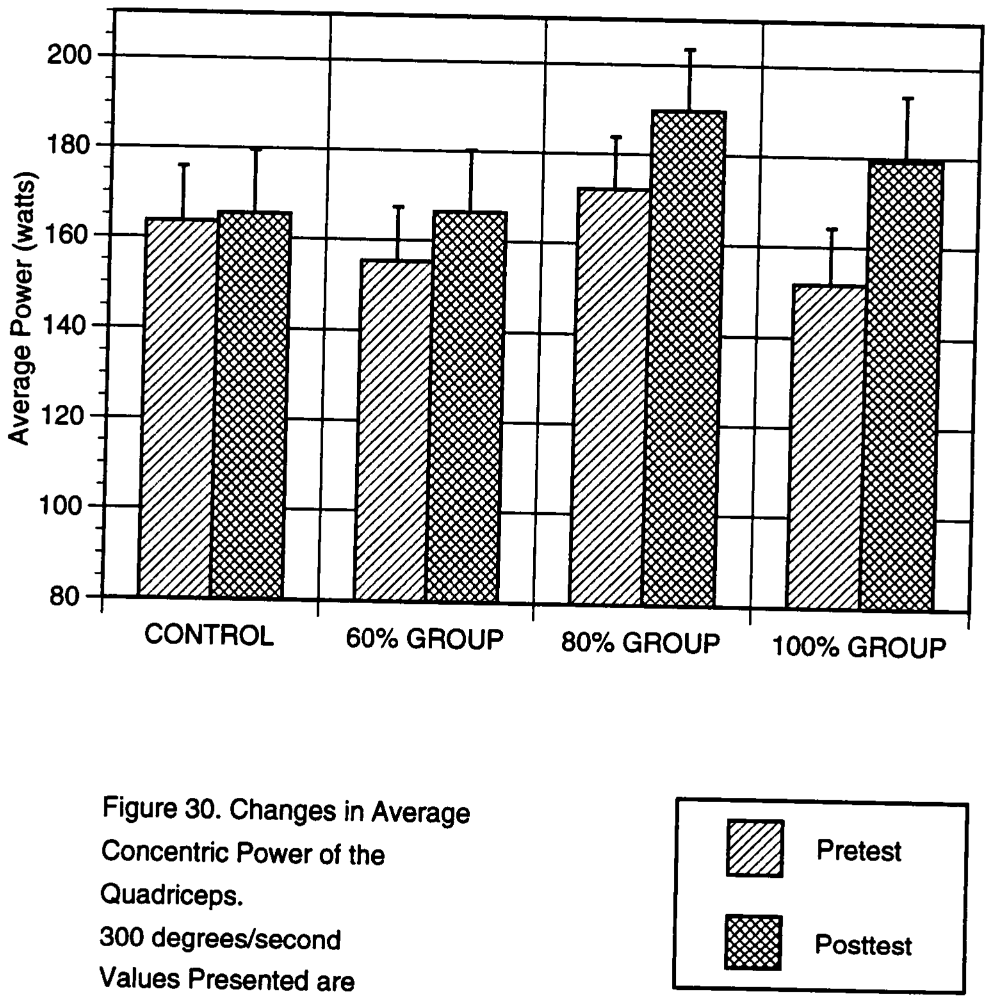


Figure 30. Changes in Average Concentric Power of the Quadriceps.
300 degrees/second
Values Presented are Adjusted Means + SE.

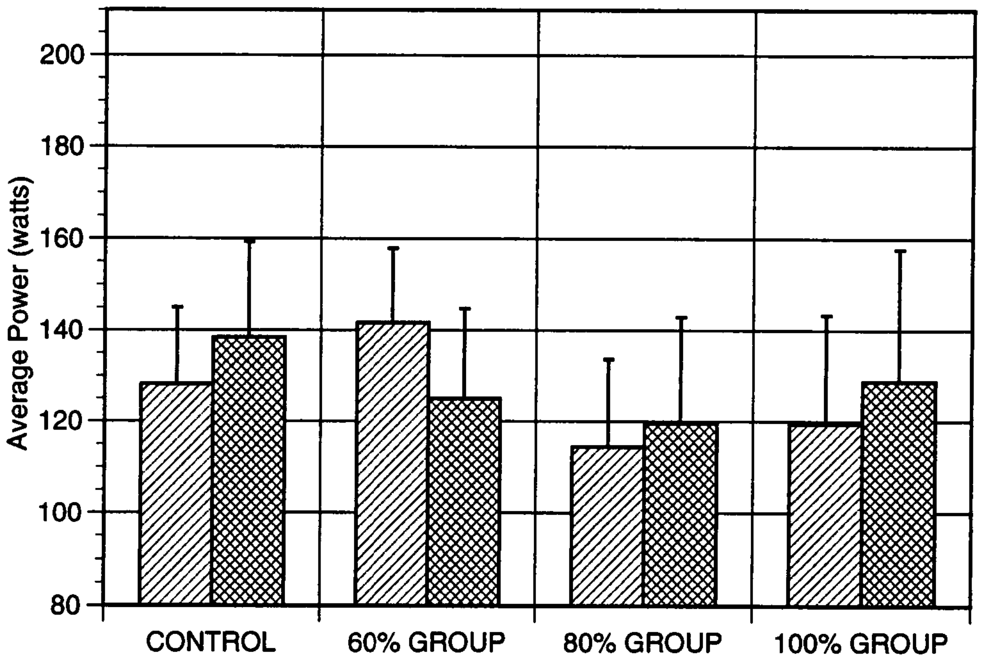
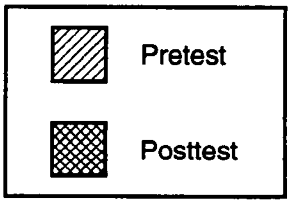


Figure 31. Changes in Average
Concentric Power of the
Quadriceps
450 degrees/second.
Values Presented are
Adjusted Means + SE.



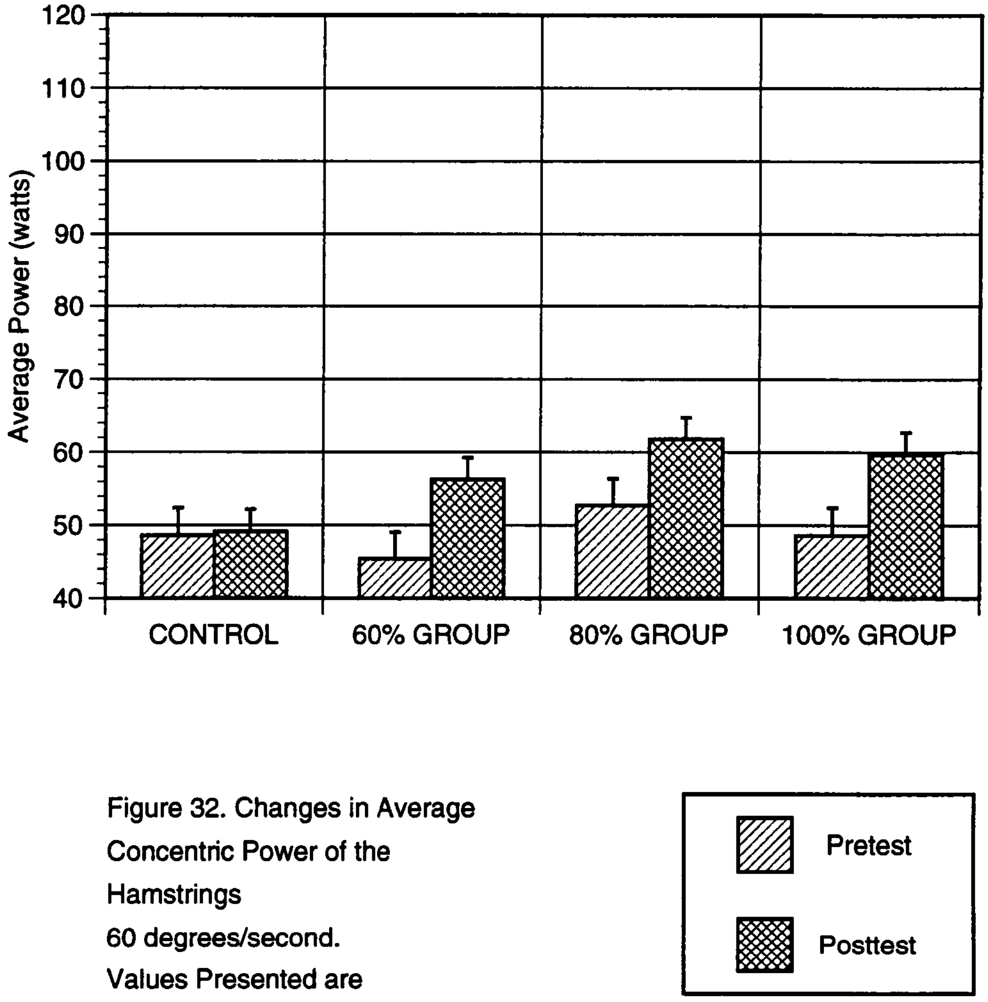


Figure 32. Changes in Average Concentric Power of the Hamstrings 60 degrees/second. Values Presented are Adjusted Means + SE.

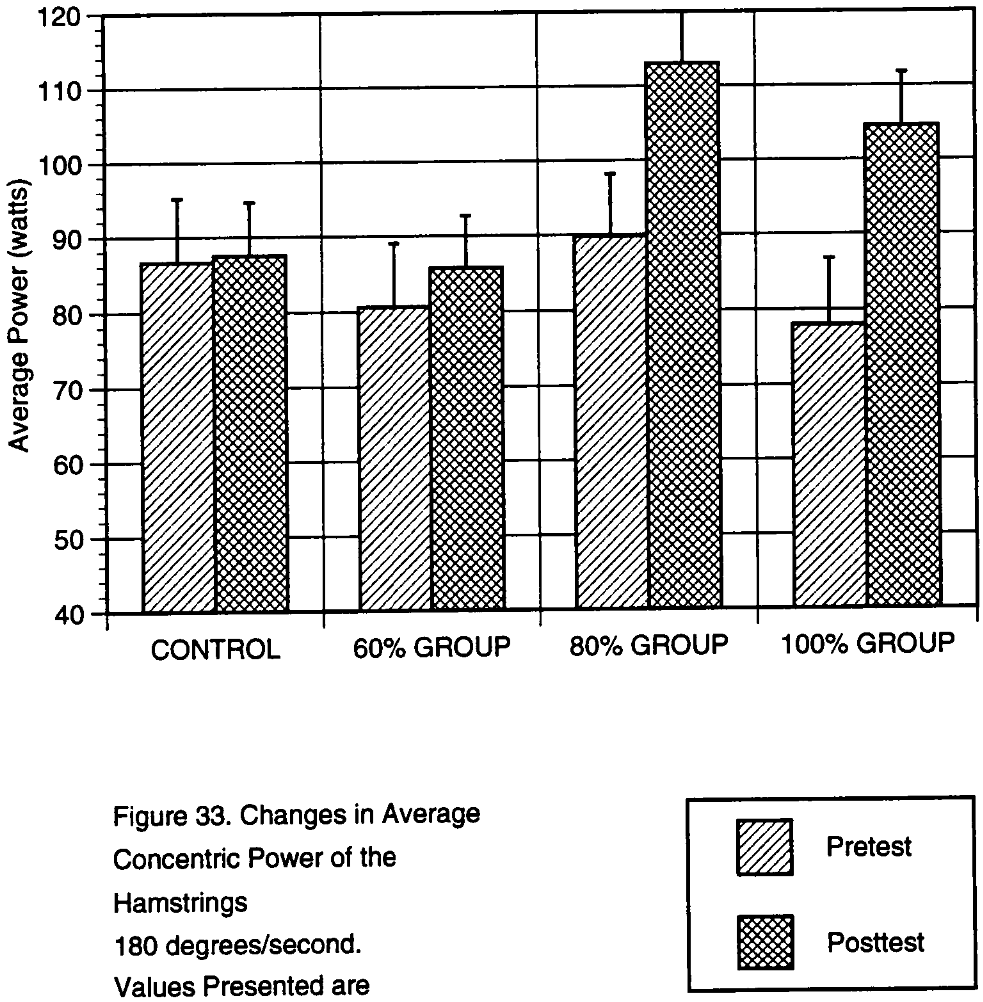


Figure 33. Changes in Average Concentric Power of the Hamstrings
180 degrees/second.
Values Presented are Adjusted Means + SE.

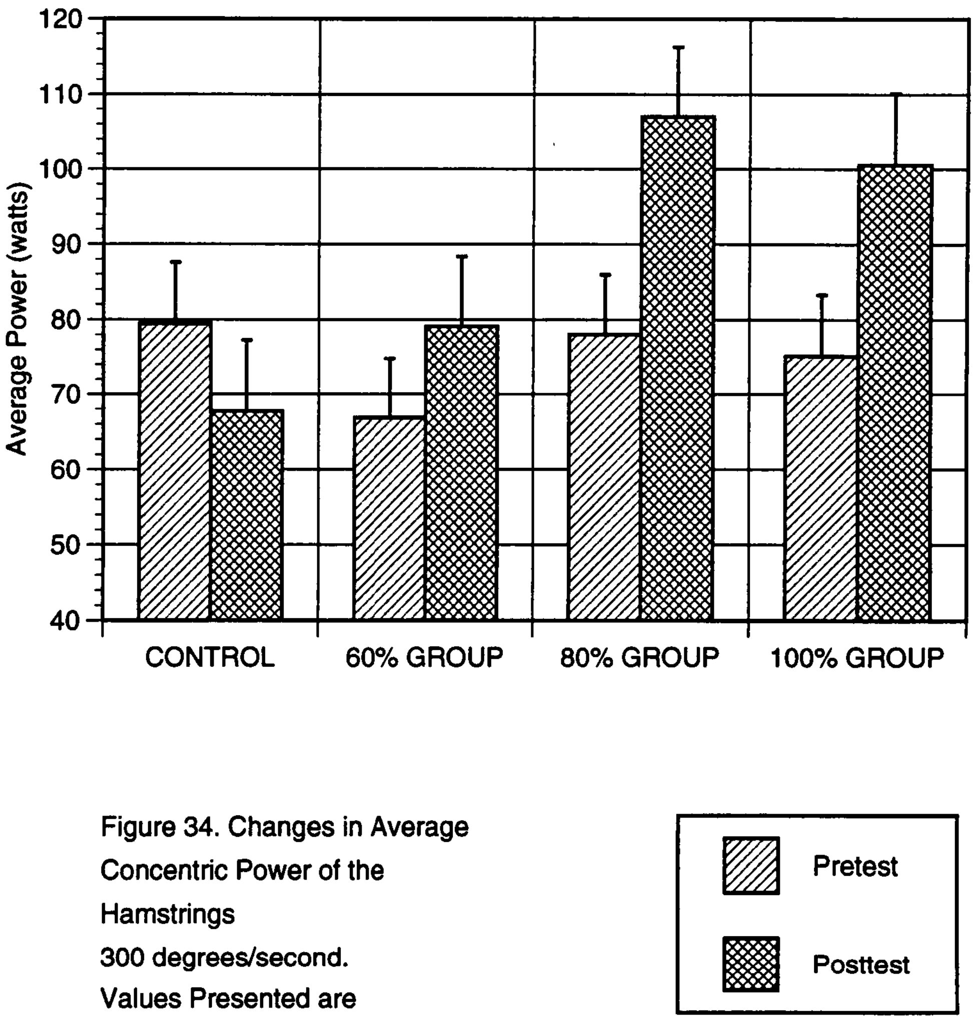


Figure 34. Changes in Average Concentric Power of the Hamstrings 300 degrees/second. Values Presented are Adjusted Means + SE.

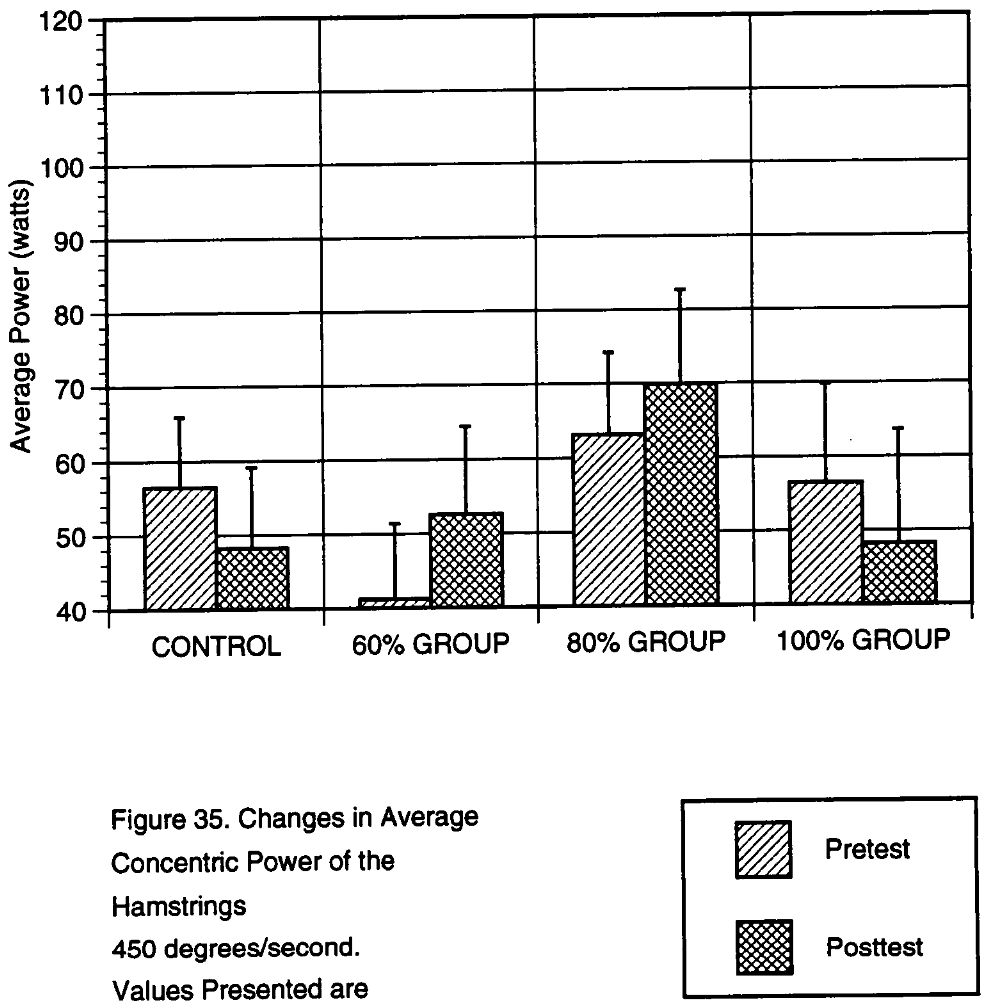


Figure 35. Changes in Average Concentric Power of the Hamstrings 450 degrees/second. Values Presented are Adjusted Means + SE.

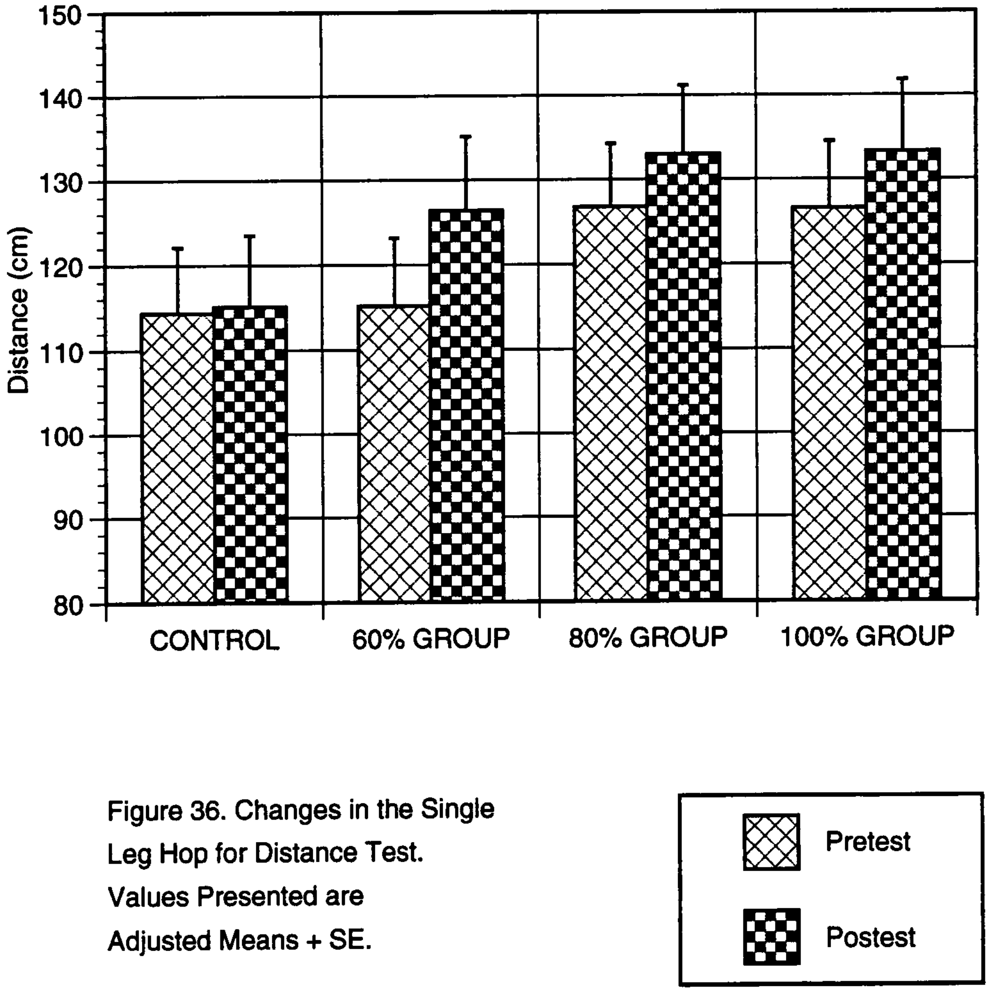


Figure 36. Changes in the Single Leg Hop for Distance Test. Values Presented are Adjusted Means + SE.

APPENDIX C

PROTOCOLS AND PROCEDURES

APPENDIX C-1
PROTOCOL FOR PART I

Initial Testing Session

1. Signing of informed consent form
2. Completion of Health Status Questionnaire
3. Drawing for assignment to exercise group
4. Height and weight assessment using a physician's scale
5. Five minute warm-up on cycle ergometer
6. Static stretch of quadriceps and hamstrings
7. Eccentric isokinetic practice session on Biodex dynamometer with left hamstrings and quadriceps at assigned percentage of maximal effort
8. Maximal eccentric isokinetic test of right hamstrings and quadriceps
9. Instructions for future days

Second Testing Session

1. Drawing of blood for CK analysis
2. Completion of Graphic Pain Rating Scale
3. Range of motion measurements
4. Muscle soreness perception testing
5. Warm-up on cycle ergometer
6. Static stretch of quadriceps and hamstrings
7. Maximal voluntary isometric contraction test
8. Eccentric isokinetic exercise bout at assigned percentage of maximal effort
9. Instructions for future days

Third, Fourth, and Fifth Testing Session

1. Drawing of blood for CK analysis
2. Completion of Graphic Pain Rating Scale
3. Range of Motion Measurements
4. Muscle Soreness Perception Testing
5. Warm-up on cycle ergometer
6. Static stretch of quadriceps and hamstrings
7. Maximal voluntary isometric contraction test

APPENDIX C-2
GRAPHIC PAIN RATING SCALE

NAME ______________________ DATE __________________

GROUP______________________ HAMSTRINGS QUADRICEPS

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Pain distracts attention during physical exertion
Painful	Pain distracts attention from routine occupation such as writing and reading
Very Painful	Pain fills the field of consciousness to the exclusion of other events
Unbearable Pain	Comparable to the worst pain you can imagine

|———————————————————————————————————|

no pain	dull ache	slight pain	more slight pain	pain-ful	very painful	unbearable pain

APPENDIX C-3
CREATINE KINASE ASSAY PROCEDURE

Creatine kinase (CK) activity was measured using the following instrumentation:

Spectronic 601 spectrophotometer set at a wavelength of 340 nm and zeroed to measure absorbance.

The cuvette chamber of the spectrophotometer was fitted with a constant temperature cuvette holder which in turn was connected to a Haake circulating pump immersed in a 30° C water bath.

An additional Beckman incubation water bath was set at 30° C.

The following procedures were carried out.

1. Prior to each period of serum examination, a standardization test was carried out using a Sigma Accutrol test kit No. A 2034. The standard in this kit provided a normal range reading of creatine kinase activity, when it was analyzed by the CK assay procedure.

2. Prior to the spectrophotometric examination of each serum sample, the spectrophotometer was referenced at 340 nm using a water blank cuvette.

3. Creatine kinase reagent was prepared and brought to incubation temperature.

4. Each serum sample was thawed completely.

5. To a 5.0 ml cuvette, 1.0 ml of CK reagent was added.

6. To the same cuvette, 0.02 ml of serum was added and mixed by inversion.

7. The cuvette was placed in a 30° C water bath and incubated for three minutes.

8. It was then placed into the spectrophotometer, and the initial absorbance (A) was read and recorded.

9. Incubation continued for 120 seconds with readings taken every 30 seconds. The final absorbance reading was taken at 120 seconds.

10. The change in absorbance was determined by subtracting initial A from final A. This value was divided by 2 to obtain the change in A (ΔA) per minute.

11. The ΔA was noted, and if the value exceeded 0.250, the sample was assayed again starting with a dilution of one part sample with one part isotonic saline. The resulting calculation was multiplied by 2 to compensate for the dilution.

Calculations for determination of creatine kinase activity were as follows:

$$\text{CK (U/L)} = \frac{\Delta A \text{ per min} \times TV \times 1000}{6.22 \times LP \times SV}$$

Where:

ΔA per min = Change in absorbance per minute at 340 nm
TV = Total volume (ml)
SV = Sample volume (ml)
6.22 = Millimolar absorptivity of NADH at 340 nm
LP = Lightpath
1000 = Conversion of units per ml to units per liter

$$\text{CK (U/L)} = \frac{\Delta A \text{ per min} \times 1.02 \times 1000}{6.22 \times 0.02}$$

$$= \Delta A \text{ per min} \times 8200$$

APPENDIX C-4
PROTOCOL FOR PART II

Pretest and Posttest Sessions

1. Signing of informed consent form (pretest only)
2. Completion of health status questionnaire (pretest only)
3. Height and weight assessment using physician's scale (pretest only)
4. Five minute warm-up on cycle ergometer
5. Thirty second static stretch of quadriceps and hamstrings
6. Completion of Graphic Pain Rating Scale
7. Single leg hop for distance test
8. Concentric isokinetic velocity spectrum test
9. Fifteen minute rest period
10. Eccentric isokinetic velocity spectrum test

APPENDIX D

Health Status Questionnaire

Name:________________________________ Age:______________

Phone:_______________________________ Date:______________

****

1. Please check (YES/NO) if you presently have or have ever been diagnosed with any of the following diseases or symptoms:

SYMPTOM	YES	NO
Coronary Heart Disease	____	______
High Blood Pressure	____	______
Any Heart Problem	____	______
Stroke	____	______
Lung Disease	____	______
Epilepsy	____	______
Seizures	____	______
Diabetes	____	______
Low Blood Sugar	____	______
Asthma	____	______
Bronchitis	____	______
Kidney Disease	____	______
Liver Disease	____	______
Hay Fever	____	______
Orthopedic Problems	____	______

2. Do you have any medical condition for which you are now receiving treatment? __________

   If yes, please explain,____

3. Are you presently taking and medications? ______________ If yes, please explain and list

   ____

4. Do you do any type of exercise? ___________ If yes, please describe type, days per week and length of exercise session ______________________________________

5. Do you have any history of injury of the right knee, quadriceps or hamstrings? ____________

   If yes, please describe ____

APPENDIX E

INFORMED CONSENT FORM - PART I

Investigator: Lorna Swanson, PT, ATC, CSCS
Department of Human Performance and Sports Studies
University of Tennessee, Knoxville 37996

Description of Project

The purpose of this project is to determine if strength and power gains can be obtained during an eight week submaximal eccentric isokinetic training program and if so, to determine the optimal submaximal effort level at which this training should occur in order to produce these gains yet minimize delayed onset muscle soreness and damage. Submaximal eccentric exercise is a lengthening of the muscles against resistance at a specified percentage of one's maximal effort and will be done on a piece of equipment that keeps your speed of exercise constant (isokinetic dynamometer).

Procedures

You will not participate in any training during the course of this study other than that described below. You may do no unusual muscular activity which might make you sore, and you may use no medications such as aspirin, ibuprofen or analgesic creams which might affect the course of muscle soreness. The experiment in which you are participating involves five separate sessions. The first is a training session in which you will be familiarized with the Biodex dynamometer, and you will practice exercise on it with your left leg. Your leg will be passively straightened and bent by the machine, and you will resist this movement with your maximal effort. This session should take about 45 minutes.

You will return one week later and exercise on the Biodex with your right leg. Before you do this exercise, however, several measurements will be taken. Your active range of motion will be measured during a straight leg raise, and a bending of the knee. You will do an isometric strength test on the Biodex at three different angles of knee bend. You will be asked to rate your muscle soreness and have a small amount of blood drawn from your arm. This procedure will be done in a safe and sterile manner. You will then do three sets of 15 repetitions, resisting the motion as you did previously. The intensity at which you exercise will be at a specified percentage of your strength as determined by your previous test. You will return to repeat the soreness ratings, the straight leg raise and knee bending test, the isometric test, and the blood test at 24, 48 and 72 hours after this exercise. Each session should take about 30 minutes. The results will be discussed with you after the testing is complete.

<u>Potential Risks and Discomfort</u>

You may experience some muscle soreness from the initial exercise bout. This should last only three to five days at the most. There is a chance that you may experience a mild muscle tear, but this is unlikely. You may experience a minimal amount of pain and/or bruising from the drawing of blood. Occasionally, persons may feel faint after blood is drawn, but this is rare. If physical injury is suffered in the course of this project, please contact the investigator, Lorna Swanson at 531-5010.

Authorization

I have read the information above and understand my role in this project as well as the risks involved. I have had the procedures explained and demonstrated to me. In addition, I am aware that:

1. My name and my results will remain confidential;
2. I am entitled to have any further inquiries answered regarding the procedures;
3. I may withdraw my consent and discontinue participation at any time without penalty or prejudice to me.
4. In the event of physical injury due to my participation in this project, financial compensation is not available and medical treatment will not be provided free of charge.

My signature also indicates that I have received a copy of this consent form.

Signature ___________________________ **Date:**_____________

Witness_______________________________ **Date:**_____________

INFORMED CONSENT FORM - PART II

Investigator: Lorna Swanson, PT, ATC, CSCS
Department of Human Performance and Sports Studies
University of Tennessee, Knoxville 37996

Description of Project

The purpose of this project is to determine if strength and power gains can be obtained during an eight week submaxial eccentric isokinetic training program and if so, to determine the optimal submaximal effort level at which this training should occur in order to produce these gains yet minimize delayed onset mescle soreness and damage. Submaximal eccentric exercise is a lengthening of the muscles against resistance at a specified percentage of one's maximal effort and will be done on a piece of exercise equipment that keeps your speed of exercise constant (isokinetic dynamometer).

Procedures

You may not participate in any strength training during the course of this study other than that described below. The project involves three different phases. First, pre-training measurements of your right hamstring and quadriceps strength will be made. Your functional strength will be tested using the single leg hop for distance test. The other strength tests will be done on a Biodex isokinetic dynamometer. After a five minute warm-up on a stationary bicycle and a short stretching period, you will be asked to hop as far as you can using only your right leg. You will then be asked to contract your hamstring and quadriceps muscles as hard as you can in two different ways at four different speeds of movement. First, you will be actively bending and straightening your knee against resistance provided by the machine. Then, your leg will be passively straightened and bent by the machine, and you will resist this movement with your maximal effort. These tests should take approximately 45 minutes.

You will then begin the training which will consist of three sets of 15 repetitions resisting the machine's passive motion as you did before. The intensity of this exercise will be at a specified percentage of your strength as determined by the previous test. This will be done three times per week for eight weeks (Monday, Wednesday Friday; or Tuesday, Thursday, Saturday). Each training session should take 10 to 15 minutes. Two days after the last training session, all the pre-training tests will be repeated and any improvements will be discussed with you.

Potential Risks and Discomfort

You will experience some muscle soreness from the initial exercise bout. This should last only three to five days at the most. There is a chance you will experience a mild muscle tear, but this is unlikely. If physical injury is suffered in the course of this project, please contact the investigator, Lorna Swanson at 531-5010. Benefits will include an assessment of your quadriceps and hamstring strength and possible increases of strength with training.

Authorization

I have read the information above and understand my role in this project as well as the risks involved. I have had the procedures explained and demonstrated to me. In addition, I am aware that:

1. My name and my results will remain confidential
2. I am entitled to have any further inquiries answered regarding the procedures
3. I may withdraw my consent and discontinue participation at any time without penalty or prejudice to me.
4. In the event of physical injury due to my participation in this project, financial compensation is not available and medical treatment wil not be provided free of charge.

My signature also indicates that I have received a copy of this consent form.

Signature ______________________________ **Date:**______________

Witness________________________________ **Date:**______________

VITA

Lorna Ellen Swanson was born in Bridgeport, Connecticut on July 22, 1954. She attended public schools in Charlotte, North Carolina, Springfield, Virginia, and Dallas, Texas and was graduated from Skyline High School in Dallas in 1971. In August, 1971, she entered Texas Christian University and in 1973, transferred to Southern Methodist University . There she received a Bachelor of Fine Arts degree in 1975 with an emphasis in Dance. She received a Master of Fine Arts degree in 1978, also from Southern Methodist University. After graduation, she taught dance at several schools in the Dallas area.

In 1983, Ms. Swanson returned to school at The University of Texas, Southwest Medical School at Dallas to pursue training in Physical Therapy. She was graduated with a Bachelor of Science degree in August, 1984. Upon graduation, she moved to Knoxville, Tennessee where she has practiced as a physical therapist in area medical centers for ten years. She was also appointed to the physical therapist assistant faculty at Roane State Community College where she taught for four years.

In September of 1985, she entered graduate school at the University of Tennessee, Knoxville in the Department of Human Performance and Sports Studies to pursue a Doctor of Philosophy degree in Education with an emphasis in Exercise Science. From 1989 to 1991, Ms. Swanson held a graduate assistantship in the Men's Athletic Department at the university. In 1991, she was certified by the National Athletic Trainers Association as an athletic trainer (A.T.,C.), and by the National Strength and Conditioning Association as a strength and conditioning specialist (C.S.C.S.).

Following graduation in December, she will remain in her present position as Manager of Sports Medicine and Clinic Coordinator of Clinical Education at Fort Sanders Regional Medical Center. She is a member of the American Physical Therapy Association, the National Athletic Trainers Association, and the National Strength and Conditioning Association.