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THE EFFECTS OF INTERMITTENT ISOMETRIC FATIGUE ON CONCENTRIC, ECCENTRIC, AND ISOMETRIC TORQUE

By

Robert Lewis, Jr.

A THESIS

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THE EFFECTS OF INTERMITTENT ISOMETRIC FATIGUE ON CONCENTRIC, ECCENTRIC, AND ISOMETRIC TORQUE

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University of Nebraska, 2013

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Fatiguing intermittent isometric (ISO) muscle actions of the leg extensors have been shown to result in a similar percent (%) decline in torque for concentric (CON), eccentric (ECC), and ISO muscle actions. However, the effects of intermittent ISO fatigue of the forearm flexors on CON, ECC, and ISO torque, have not been established. The purpose of this investigation was to determine the effects of 50 maximal, intermittent ISO forearm flexion muscle actions on CON, ECC, and ISO torque. Twenty adults (10 men (mean ± SD age = 21.9 ± 2.3 years) and 10 women (mean ± SD age = 22.7 ± 2.6 years) volunteered to perform 50 consecutive, intermittent ISO forearm flexion muscle actions. Before and after the fatiguing workbouts, peak torque (PT) was measured (randomly ordered) for CON, ECC, and ISO muscle actions. Polynomial regression analysis indicated a quadratic (R^2 = 0.97) pattern of responses during the 50 intermittent ISO muscle actions. There were no differences in mean % decline (29%) in torque values among the three types of muscle actions. The current findings indicate that the CON, ECC, and ISO muscle actions share a common mechanism of fatigue as a result of the fatiguing intermittent ISO workbout.

DEDICATION

I dedicate this thesis to my wife, Beatriz, who was willing to leave her career as a Pharmacist, her family, and her friends to support my education. Without her, I would not have realized my potential and this thesis would not have been possible. I also dedicate this thesis to my two children Robert, and Sebastian, who have not seen much of me during the completion of this project. It is through your smiling faces that I have found the strength to work the hardest I ever have. Everything I do is for the love of my wife and children.

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Chapter I

Introduction

Fatigue has been defined as "…any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (7, p. 691). A number of previous investigations have examined the effects of fatigue induced by one type of muscle action (e.g. concentric) on the peak torque (PT) produced by different types of muscle actions (e.g. eccentric or isometric) (5, 10, 12, 15, 23, 25, 28, 30, 32, 37, 41, 42, 46). Most previous studies have only examined the mode-specific effects of fatiguing concentric (CON) or eccentric (ECC) workbouts (5, 10, 23, 28, 32, 37, 41, 42, 46). For example, Lewis et al. (28) reported no mode-specific effects on CON isokinetic, ECC isokinetic, or maximal voluntary isometric contraction (MVIC) PT following a fatiguing workbout of 50 maximal CON isokinetic muscle actions of the forearm flexors at $180°\cdot s^{-1}$. In addition, Beck et al. (5) reported no differences in the percent decline of CON isokinetic, ECC isokinetic, or MVIC PT following separate bouts of 30 maximal CON or ECC isokinetic muscle actions of the forearm flexors at $30°\cdot s^{-1}$. In contrast, Linnamo et al. (30) reported that a CON isokinetic fatiguing workbout of 100 muscle actions of the forearm flexors at $115°\cdot s^{-1}$ elicited a 19% greater decline in CON isokinetic PT than ECC isokinetic PT and a fatiguing workbout of 100 ECC isokinetic muscle actions elicited a 27% greater decline in ECC isokinetic PT than CON isokinetic PT (30). In addition, Semmler et al. (42) reported that following a CON or ECC dynamic constant external resistance (DCER) fatiguing workbout (mean ± SD = 170 ± 37 and 146 ±17 repetitions, respectively), MVIC declined 45% and 22%, respectively. Thus, conflicting evidence exists regarding the mode-specific nature of decreases in PT

following fatiguing workbouts. The mode-specific declines in PT from previous studies (5, 28, 30, 42) may have been due to factors such as the velocity of the muscle actions, the number of repetitions performed, and fatigue induced by continuous versus intermittent muscle actions. In addition, previous investigations (6, 12, 28, 32) have reported different ranges of % declines in PT for the arms versus the legs. For example, studies conducted on the forearm flexors (6, 28) have reported 25-30% declines following CON isokinetic and ECC isokinetic fatiguing workbouts. In contrast, investigations of the leg extensors (12, 32) reported 8-17% declines in PT following CON isokinetic and ECC isokinetic fatiguing workbouts. Thus, PT production following a fatiguing workbout may depend on the muscle group involved (i.e. forearm flexors vs. leg extensors) and the type of muscle action (CON, ECC, or ISO) tested.

Mode-specific decline in PT has been attributed to the build-up of metabolic byproducts and/or damage to the myofibrils caused by CON, ECC and/or ISO muscle actions. For example, it has been suggested (12, 16, 20, 28), that fatigue resulting from CON or ISO muscle actions may be due to build-up of metabolic by-products (i.e. ammonia, hydrogen ions, potassium, and/or inorganic phosphate), whereas fatigue resulting from ECC muscle actions may be due to both the build-up of metabolic by-products and damage to the myofibril (i.e. sarcomere derangement, fragmented or swollen sarcoplasmic reticular elements, dilated T-tubules, and lesions in the plasma membrane) (45). Therefore, different mechanisms of fatigue may be responsible for the muscle action specific responses to fatiguing workbouts.

Many studies have investigated the mode-specific effects of CON and/or ECC fatiguing workbouts on PT of the leg extensors and forearm flexors. Only one

investigation (12), however, has investigated mode-specific changes in PT resulting from a fatiguing workbout of maximal intermittent ISO muscle actions. Camic et al. (12) reported that the % decline in PT was similar among the three types of muscle actions tested (CON, ECC, and ISO) following a fatiguing workbout of 30 maximal intermittent ISO muscle actions of the leg extensors. Thus, the results of Camic et al. (2012) indicated that for the leg extensors, fatiguing intermittent ISO muscle actions had no mode-specific effects on PT. No investigations, however, have examined the mode-specific effects of fatiguing intermittent ISO muscle actions in the forearm flexors. Therefore, the purpose of the present study was to determine the effects of 50 maximal intermittent ISO muscle actions of the forearm flexors on CON isokinetic, ECC isokinetic, and MVIC PT. Based on previous studies (5, 12, 28), we hypothesized that there would be similar % declines in CON isokinetic, ECC isokinetic, and MVIC PT following the fatiguing intermittent ISO workbout.

Chapter II

Review of literature

1. Mode-specific Response to Fatiguing Muscle Actions

Michaut et al. (32)

The purpose of this study was to examine fatigue and recovery profiles following CON isokinetic fatiguing exercise. Nine females (mean ± SD age = 22.3 ± 1.2 years) volunteered to perform maximal, voluntary CON, ECC, and ISO muscle actions of the leg extensors at $60°\cdot s^{-1}$ and $120°\cdot s^{-1}$ for determination of PT before and after ten sets of ten maximal, CON, isokinetic leg extensions at $60°\cdot s^{-1}$ using a Biodex System 3 isokinetic dynamometer. The results demonstrated decreases in CON torque (7% and 1%) and ECC torque (14% and 21%) at $60°\cdot s^{-1}$ and $120°\cdot s^{-1}$, respectively. In addition, ISO torque decreased 10.7% following the fatigue protocol. The authors suggested that the decline in ECC and ISO torque following the CON fatiguing workbout may have been due to both peripheral and central fatigue. In addition, they concluded that torque recovery was dependent on the type of muscle action.

Tesch et al. (46)

The purpose of this study was to compare torque during repeated bouts of consecutive, maximal CON and ECC muscle actions of the leg extensors. Fourteen males (mean ± SD age = 33 ± 2 years) volunteered to visit the lab on two separate occasions. During each visit subjects performed two MVIC's at an angle of 45° separated by one minute of rest for assessment of peak torque. The mean values of the MVIC's for visits

one and two were 224 ± 14 and 221 ± 14 Nm, respectively and test-retest reliability was r = 0.96. Following the MVIC's, subjects performed three bouts of 32 maximal CON or ECC isokinetic muscle actions of the leg extensors at a velocity of $180°\cdot s^{-1}$. The results indicated that the ECC muscle actions resulted in greater torque values throughout the test compared to the CON muscle actions (200 Nm versus 100Nm, respectively). During the CON workbouts torque decreased in a linear fashion (range of % declines = 34 - 47%). In contrast, torque increased slightly within each of the three ECC workbouts. The authors suggested that during the repeated CON muscle actions, the decreases in torque were likely the result of impaired actin-myosin cross-bridge formation. In addition, it was suggested that the greater mechanical efficiency associated with ECC torque production (i.e. the increase in torque during the workbouts) was the result of stored elastic energy in the actin-myosin cross-bridges.

Kay et al. (25)

The purpose of this study was to examine fatigue during CON, ISO, and ECC muscle actions of the leg extensors. Twelve subjects (mean ± SD age = 21.7 ± 3.7 years) volunteered to perform three separate, 100-second fatiguing workbouts of CON, ECC, and ISO muscle actions. Prior to the fatiguing workbouts, subjects were tested for CON ($60°\cdot s^{-1}$), ECC ($60°\cdot s^{-1}$) and ISO (at an angle of 60° with 0 being full extension) PT. Following the determination of PT, subjects underwent one of the three 100-second fatiguing workbouts. During these workbouts, the CON and ECC, isokinetic muscle actions were performed at $60°\cdot s^{-1}$ with two seconds of passive flexion between each contraction and the ISO contractions were performed at an angle of 60°. The authors reported no significant differences in PT between CON (169.2 ± 41.1 Nm), ISO (177.2 ±

61.1 Nm), and ECC (211.1 ± 63.1 Nm) muscle actions. During the fatigue protocols, there was a significant decrease in normalized torque for the CON (57.7% ± 15.3%) and ISO (30.5% ± 12.7%) muscle actions, but torque was maintained during the ECC workbout (108.6% ± 3.9%). It was concluded that factors such as the elastic component of muscle, incomplete motor unit activation, selective recruitment of fatigue-resistant fibers, and greater muscle temperatures may explain the fatigue resistant nature of ECC muscle actions.

Linnamo et al. (30)

The purpose of this study was to examine the effects of repeated, maximal CON and ECC muscle actions on maximal ECC and CON force production immediately following repeated exercise bouts. Eight male subjects (age range = 21 – 33 years) volunteered to perform two maximal CON and ECC muscle actions of the forearm flexors before and after 100 repeated ECC or CON muscle actions at $115°\cdot s^{-1}$ on two separate occasions using an isokinetic dynamometer. Prior to the test, the subjects performed maximal ECC and CON muscle actions. It was reported that ECC torque (300 Nm) was greater than CON torque (200 Nm) before the exercises. In addition, CON and ECC force production decreased 38.4% ± 4.0% and 53.3% ± 3.5%, respectively, following the fatiguing ECC workbout. However, after the repeated CON muscle actions, CON and ECC force decreased 49.9% ± 6.6% and 30.6% ± 6.4%, respectively. There was a greater absolute decrease in ECC PT following the ECC fatigue protocol compared to the absolute decrease in CON PT following the CON fatigue protocol. The authors concluded that the ECC muscle actions led to possible muscle damage leading to a longer recovery compared with CON muscle actions. Therefore, it was suggested that fatigue

was dependent upon the type of muscle action (i.e. CON versus ECC) that was implemented during the fatigue protocol.

Nosaka and Newton (37)

The purpose of this study was to investigate the loss of maximal strength immediately after exercise would correlate with changes in other markers of muscle damage following ECC exercise. Eighty-nine subjects (mean ± SD age = 20.5 ± 2.8 years) volunteered to perform two, three second ISO maximal voluntary contractions (MVCs) of the forearm flexors (at a joint angle of 90°, 180° being full extension) before and after 24 maximal ECC muscle actions using a specially designed arm curl machine. The examiner forcibly extended the subjects forearm from a flexed position (90°) to an extended position (180° i.e. full extension) in three seconds. Torque was measured using a load transducer which was attached to the wrist of the subjects. The authors reported that the pre-fatigued ISO MVCs (180.3 ± 36.3 N) decreased 50.1% ± 11.3% after the maximal ECC muscle actions. On days one and four after the fatiguing workbout, subjects experienced a slight recovery, but the decrease in torque was still 45.5% and 37.2% less than the pre-fatigued ISO MVC values. It was suggested that although the mechanisms underlying ECC exercise-induced muscle damage remain unclear, it is likely the result of impaired membrane systems, myofibrils, and/or cytoskeleton elements that are associated with the repeated mechanical stresses of ECC muscle actions.

Camic et al. (12)

The purpose of this study was to compare the effects of fatiguing CON, ISO, and ECC actions of the leg extensors. Twelve females (mean ± SD age = 21.1 ± 1.4 years)

performed 30 repeated maximal CON, ISO, and ECC repetitions of the leg extensors using a Cybex 6000 isokinetic dynamometer. Peak torque for CON and ECC muscle actions at $30°\cdot s^{-1}$ and for ISO muscle actions sustained for three seconds at a joint angle of 120° (between the thigh and leg) were determined before and immediately after each fatigue protocol. Immediately after the determination of PT, the subjects performed one of the three fatigue protocols which consisted of 30 repeated, maximal muscle actions followed by a three second passive leg flexion or extension (during the CON or ECC fatigue protocol) or 3 seconds rest (during the ISO fatigue protocol). For the intermittent ISO fatigue protocol, the maximal, ISO muscle actions of the leg extensors were sustained for three seconds and performed at a joint angle of 120°. The authors reported that for the peak torque measured prior to the ISO fatiguing protocol, ECC torque (197.7 N·m) was the highest, followed by ISO torque (177.4 N·m) and CON torque (169.6 N·m). Following the ISO fatiguing protocol, ECC torque remained the highest followed by ISO and CON torque, respectively. In addition, during the CON and ISO fatiguing protocols, there were significant decreases in torque ($R^2 = 0.97$; $R^2 = 0.95$, respectively) from the first repetition to the 30th repetition. During the ECC fatigue protocol, however, torque did not decrease to the same extent as that of the others ($R^2 = 0.60$). The authors suggested that the decline in torque across the different fatigue protocols were likely the result of the muscle damage and mechanical efficiency related to repeated ECC muscle actions.

Lindstrom et al. (29)

The purpose of this study was to assess muscle fatigue and endurance of the leg extensors in younger and older men and women. Twenty-two young (mean ± SD age =

28 ± 6 years) and 16 older (age = 73 ± 3 years) subjects volunteered to perform 100 repeated maximal leg extensions at $90°\cdot s^{-1}$ using a Cybex II isokinetic dynamometer. Prior to the fatigue test, the subjects performed three maximal voluntary (MVC) CON isokinetic muscle actions at $90°\cdot s^{-1}$. The authors reported that MVC was significantly lower in the older group compared to the younger group (112 Nm versus 180 Nm, respectively). In contrast, there were no significant differences in relative muscle force reduction and fatigue rate between the younger and older groups. During the fatiguing muscle actions, a plateau in torque occurred at about the 40th repetition. In addition, the fatigue index of the young men was 39, while the older men manifested a fatigue index of 55. The young women also had a greater fatigue index than the older women (55 versus 48, respectively). The authors concluded that the leg extensor muscle group of older individuals was weaker than those of younger individuals, relative to strength, however, older individuals have similar properties as younger individuals with respect to muscle fatigue and endurance.

Beck et al. (5)

The purpose of this investigation was to examine the strength responses after workbouts designed to elicit fatigue and muscle damage versus only fatigue. Thirteen men (mean ± SD age = 23.7 ± 2.2 years) volunteered to perform six sets of 10 maximal CON isokinetic or ECC isokinetic muscle actions of the dominant forearm flexors at a velocity of $30°\cdot s^{-1}$ on two separate days. Before and after these workbouts, PT was measured during maximal CON and ECC muscle actions at a velocity of $60°\cdot s^{-1}$ and ISO muscle actions for 6 seconds at a joint angle of 90° (180° being full extension) of the forearm flexors. The authors reported that there were significant decreases in PT after the

CON (26%) and ECC (25%) exercise, respectively. Furthermore, these decreases were statistically equivalent for the CON, ECC, and ISO muscle actions. The authors concluded that the strength reductions following the fatiguing workbouts were not specific to any single type of muscle action.

Semmler et al. (42)

The purpose of this study was to determine the effect of ECC and CON exercise on the ability to exert steady submaximal forces with the forearm flexors. Seven men and three women (mean ± SD = 30.9 ± 2.6 years) volunteered to perform two separate fatiguing workbouts of CON and ECC muscle actions. A maximal voluntary contraction (MVC) and a constant-force task at four submaximal target forces (5, 20, 35, 50% MVC) was performed before, after, and 24 hours after a period of ECC or CON exercise. The ECC and CON exercise was performed using a standard preacher-curl bench where the right arm was positioned at a 45° angle from the torso. For the ECC exercise, the weight (equivalent to 40% of the ISO MVC at 90°) was placed in the hand of the subjects, and the subjects subsequently lowered the weight from an elbow joint angle of 45° to full extension (180°) within 2 seconds, followed by a 4 second rest. For the CON exercise, the subjects lifted the load from full forearm extension (180°) to an elbow joint angle of 45°, with 3 seconds to perform the muscle action and a 3 second rest in between contractions. Following the CON contraction, the load was removed by the experimenter and the arm was returned to full extension. The load lifted during the CON contraction was equivalent to 30% of the MVC at 90°. For both ECC and CON exercise protocols, ten contractions were performed followed by 20 seconds of rest between sets. The contractions continued until the subject could no longer lift or maintain control of the

load. The authors reported that the MVC force declined after the ECC exercise (45% decline) and remained depressed 24 hours later (24%), whereas the reduced force after the CON exercise (22%) fully recovered the following day. It was concluded that ECC exercise resulted in muscle damage which prolonged the recovery process, whereas CON exercise resulted in only metabolic fatigue which allowed a faster recovery.

Cleak and Eston (15)

The purpose of this study was to describe changes in ISO strength, arm swelling, muscle tenderness and perceived soreness over 11-days following ECC exercise. Twenty-six female subjects (mean ± SD = 21.4 ± 3.3 years) volunteered to perform a fatiguing workbout of 70 maximal ECC muscle actions of the forearm flexors. Prior to and following the fatiguing workbout, subjects underwent three, 5-sec ISO maximal voluntary contractions (MVCs) before and immediately after 70 maximal ECC muscle actions of the forearm flexors. In addition, isometric strength loss was tested during the 11 days following the ECC protocol. The investigators reported no association between pain and strength loss throughout the 11-day period. Thus, it was suggested that pain and soreness were not responsible for the impairment in force production. Furthermore, despite the significant reduction in ISO strength immediately following the ECC exercise, there was no pain experienced by the subjects. Therefore, the authors attributed the ISO force decrements to ECC-induced muscle damage including the actin becoming detached from the z-band, thus limiting the sarcomeres ability to contract.

Sayers and Clarkson (41)

The purpose of this investigation was to examine force loss and recovery in a group of male and female subjects and characterize individuals who suffer prolonged consequences during ECC exercise protocols. One hundred ninety subjects (mean ± SD = 25.0 ± 0.4 years) volunteered to perform three, 3-sec ISO maximal voluntary contractions (MVCs) of the non-dominant forearm flexors at an elbow angle of 90° before and after 50 maximal, ECC muscle actions. The ECC muscle actions were conducted using a modified lever machine where the investigator pulled down on a lever causing forced forearm extension. Isometric force was measured using a strain gauge. The investigators reported a mean ISO strength decrease of 57% following the ECC fatiguing protocol. In addition, 32 (17%) subjects demonstrated 70% reductions in ISO MVC as well as prolonged recovery time to attain the pre-fatigued maximum force level. It was suggested that the greater reductions in MVC torque following the ECC fatigue protocol for the females compared to the males may have been due to greater muscle damage associated with lack of training. Furthermore, the authors suggested that the females may have provided greater effort to maintain maximal exertion throughout the entire protocol than the males, thus increasing the amount of muscle damage.

Hamlin and Quigley (23)

The purpose of this investigation was to determine the effect of bench-stepping on the strength and endurance of the leg extensors before and during delayed-onset muscle soreness. Ten males (mean ± SD = 25 ± 5 years) performed 30-sec sustained, maximal ISO muscle actions of the leg extensors at an angle of 115° between the thigh and leg.

The ISO MVCs were performed for both legs before and immediately after 20 minutes of bench-stepping with a constant leading leg. The bench-stepping protocol was designed so that the leading leg was exercised concentrically and the trailing leg was exercised eccentrically. The investigators reported that ECC-fatigued MVCs resulted in greater decreases (mean ± SE = 88% ± 2% of the pre-fatigued value) compared to the CON-fatigue MVCs. No significant differences existed, however, for the fatigue index during the 30-sec sustained MVCs between the ECC- and CON-fatigued legs. The authors suggested that CON fatigue is likely the result of end-products of metabolism, such as lactate and H^+ that affect the actin-myosin interaction and reduce the sarcomere's ability to maximally contract. It was also suggested that ECC exercise is less metabolically demanding and results in less lactate production compared to CON exercise.

Byrne et al. (10)

The purpose of this investigation was to determine how reductions in ISO force following ECC exercise were affected by the muscle length at which force was measured; and to compare the effect of exercise-induced muscle damage on ISO and CON strength at slow and fast velocities of movement. Five males and three females (mean ± SD = 21.4 ± 3.5 years) volunteered to perform maximal voluntary ISO muscle actions at joint angles of 10 and 80° (0° being full extension) and maximal CON, isokinetic muscle actions at 30 and $180°\cdot s^{-1}$ for determination of PT before and after ten sets of ten maximal, ECC isokinetic leg extensions at $90°\cdot s^{-1}$ using a Kin-Com isokinetic dynamometer. The authors reported that the 100 ECC muscle actions of the leg extensors resulted in a 65.4% (10°) and 70.3% (80°) reduction in ISO torque, as well as a 76.8% ($30°\cdot s^{-1}$) and 70.3% ($180°\cdot s^{-1}$) reduction in CON torque. It was suggested that the greater ISO strength loss at

10° compared to 80° indicated that ECC exercise resulted in a shift to the right (i.e. towards the longer muscle lengths) in the length-tension curve. It was also suggested that the strength loss related to the ECC muscle actions may have been due to over-stretching of sarcomeres, thereby decreasing the number of cross-bridges capable of force generation. In addition, the greater decrease in CON strength at $180°\cdot s^{-1}$, compared to $30°\cdot s^{-1}$, indicated that fatiguing ECC activity may result in the selective damage of fast twitch muscle fibers.

Lewis et al. (28)

The purpose of this study was to determine the effects of 50 maximal CON, isokinetic muscle actions of the forearm flexors on CON, ECC, and ISO torque. Eight men (mean ± SD = 23.1 ± 2.3 years) and eight women (mean ± SD = 22.8 ± 1.4years) volunteered to perform 50 consecutive maximal, CON isokinetic muscle actions of the forearm flexors at $180°\cdot s^{-1}$ using a Cybex 6000 isokinetic dynamometer. Peak torque (PT) was measured before and after the fatiguing workbouts during maximal CON isokinetic, ECC isokinetic, and ISO muscle actions. The authors reported significant declines in CON (% decline = 38%), ECC (% decline = 23%), and ISO (% decline = 28%) torque following the fatiguing workbout. There were no differences in the percent declines between the three types of muscle actions. It was suggested that the fatiguing workbout resulted in a build-up of metabolic byproducts which were responsible for the similar declines in torque in the three types of muscle actions.

2. Mode-specific Differences in PT

Griffin et al. (22)

The purpose of this investigation was to describe torque-velocity relationships during CON, ECC, and ISO testing of the forearm flexors. Thirty women (mean ± SD = 27.3 ± 6.9 years) volunteered to perform maximal voluntary ISO muscle actions at a joint angle of 90° (0° being full extension) and maximal, voluntary CON and ECC, isokinetic muscle actions at 30, 120 and 210°·s^{-1} using a Kin-Com isokinetic dynamometer for determination of PT of the forearm flexors. Subjects performed three sets of consecutive maximal CON and ECC muscle actions with no rest between efforts. Isokinetic muscle actions were performed from 40° to 120° and the sequence of testing was from slow to fast. For isometric testing, the subjects elbow was positioned at a 90° angle and the three maximal contractions lasted three seconds with one second of relaxation between contractions. The findings indicated that ECC forearm flexion PT (mean PT = 37.6 Nm, collapsed across velocity) was greater than CON PT (30.36 N·m, collapsed across velocity) and ISO PT (35.51 N·m). For CON muscle actions, the greatest torque was produced at 30°·s^{-1} (34.07 N·m), followed by 120°·s^{-1} (30.09 N·m) and 210°·s^{-1} (26.93 N·m). For the ECC muscle actions, however, the greatest torque was produced at 120°·s^{-1} (39.09 N·m) followed by 30°·s^{-1} (38.03 N·m) and 210°·s^{-1} (35.61 N·m). It was suggested that the decrease of ECC torque from 120°·s^{-1} to 210°·s^{-1} could have been due to the limited range of motion (40° - 120°) which may not have allowed subjects enough time to generate maximal ECC PT at 210°·s^{-1}.

Mawdsley and Knapik (31)

The purpose of this investigation was to describe variations in maximal torque produced by leg extension and flexion, as well as forearm extension and flexion during isometric, isotonic, and isokinetic muscle actions. Sixteen men (mean ± SD = 26.1 ± 3.8 years) and 15 women (mean ± SD = 24.9 ± 4.1 years) volunteered to visit the laboratory on five separate occasions to be tested on one of the four muscle groups. During the first week, subjects were familiarized with the testing procedures. During weeks two through five, subjects reported to the laboratory one day per week and one of the four muscle groups was tested (i.e. leg flexors, leg extensors, forearm flexors and forearm extensors). Isokinetic testing was performed using a modified Cybex apparatus. For isometric leg extension and flexion, subjects performed one contraction every 10° (0° being full extension) from 90° to 20°. For isometric forearm flexion and extension, subjects performed one muscle action at 30º (0° being full extension), 50 º, 70 º, 90 º, 110 º, and 120°. In addition, isokinetic muscle actions were performed at 36, 108, and $180°\cdot s^{-1}$ for all four muscles. One-repetition maximum was used to assess isotonic strength. The authors reported that ISO torque was the highest throughout the entire range of motion for all muscle groups tested, with isotonic torque demonstrating the second highest torque. In addition, as isokinetic velocity increased, torque decreased. Specifically for forearm flexion, isometric torque increased from 30° to 50°, plateaued from 50 to 90°, and declined thereafter. Furthermore, isokinetic torque for forearm flexion, gradually increased through the range of motion until reaching PT at 70°, and declined thereafter. In the male subjects, forearm flexion and extension PT was measured at an angle of 90° for isotonic and ISO muscle actions, and at 70° for isokinetic muscle actions. Females,

manifested different angles of PT for forearm flexion versus extension. For forearm extension in the female group, PT occurred at an angle of 90° for isotonic muscle actions, and 70° for ISO, and isokinetic muscle actions at all velocities tested. For forearm flexion in the female group, PT occurred at an angle of 90° for isotonic, ISO, and isokinetic muscle actions at 36 and $108°\cdot s^{-1}$. Peak torque for forearm flexion at a velocity of $180°\cdot s^{-1}$ for females was produced at an angle of 70°. In addition to the mean torque values presented by the authors, a high degree of individual variability was found for both the angles at which PT occurred, as well as the shape of the curves for the torque, angle relationships. Therefore the authors suggested that patients in a rehabilitative setting be assessed individually for their own unique torque curves. In addition, the authors suggested that the individual isometric curves could be used to estimate one repetition max, as well as the angle at which PT for isotonic muscle actions occurs. It was further suggested that if individual assessment is not possible, the data from the current study could be used as a general guide for their patients and that large variations from the curves (i.e. torque versus angle relationships) reported in this study may indicate functional loss from injury or disease.

Knapik and Ramos (26)

The purpose of this investigation was to describe the relationship between isometric and isokinetic strength testing. Three hundred and fifty two males (mean ± SD = 23.6 ± 5.5 years) volunteered to perform maximal isometric and isokinetic muscle actions of the forearm flexors, forearm extensors, leg flexors, and leg extensors. For ISO forearm flexion and extension, the tests were performed at a joint angle of 90° (0° being full extension). For ISO leg flexion and extension, the tests were performed at a joint

angle of 160° and 120°, respectively. The isokinetic muscle actions were performed using a Cybex II dynamometer, and were conducted at velocities of 30, 90, and $180°\cdot s^{-1}$. Subjects were tested for ISO peak torque, followed by the three isokinetic contractions with a one minute rest between each contraction. The authors reported that for all muscle groups tested, as angular velocity increased, torque decreased. Isometric torque production was the greatest, followed by 30, 90, and $180°\cdot s^{-1}$, respectively. It was suggested that the torque velocity relationships may have been due to the time allotted for recruitment of fast twitch and/or slow twitch muscle fibers. For the ISO muscle actions and the slower isokinetic velocities, recruitment of both fast twitch and slow twitch muscle fibers may have occurred which would have led to greater torque production. At the faster isokinetic velocities, however, only fast twitch muscle fibers may have been recruited, thus producing lesser torque values than the slower velocities.

Murray et al. (35)

The purpose of this investigation was to establish strength standards of the leg extensor and flexors of healthy men for comparison with performance of male patients over selected age ranges. Seventy-two men (range age = 20 – 86 years) volunteered to perform maximal isokinetic leg extension and flexion muscle actions with their right leg at $36°\cdot s^{-1}$, as well as maximal isometric leg extension and flexion muscle actions at 30, 45, and 60° (5 second contraction followed by 90 seconds rest). Subjects were divided into three age groups, youngest (N = 24, range age = 20 – 35 years), middle (N = 24, range age = 50 – 65 years), and oldest (N = 24, range age = 70 – 86 years) group. Subjects were tested for leg flexion followed by leg extension. Half the subjects started with ISO muscle actions while the other half started with isokinetic muscle actions. All

testing was conducted using a Cybex II isokinetic dynamometer. The authors reported that mean maximal isometric (140 N) torque for each joint position was significantly greater than the mean maximal isokinetic (102 N) torque. Maximal torque for all subjects during isometric and isokinetic muscle actions was produced at angles of 60 and 45°, respectively. The highest torque was produced by the youngest group followed by the middle and oldest groups, respectively. The authors suggested that the normal results of in this study provide examples of strength levels during rehabilitative efforts and how they differ with age. They suggested that age specific standards for torque be used when assessing patients and tracking their progress throughout a rehabilitative program.

Doss et al. (17)

The purpose of this investigation was to measure the maximum force of the forearm flexors continuously during CON and ECC movements and compare them with the force measured isometrically at the same angles. Thirty-seven men volunteered to perform maximal CON, ECC, and ISO muscle actions of the forearm flexors with a custom made dynamometer used to measure torque production during isotonic contractions. Each subject was given three tests, repeated three times during a single session. The three tests consisted of CON and ECC forearm flexion (at an angle between 75 and 165 degrees, 0° being full extension), as well as ISO forearm flexion at 87 and 165 degrees. The CON and ECC muscle actions lasted 18 seconds each, and the ISO muscle action lasted for at least 1 second at each joint angle. The authors reported that at all joint angles, ECC torque was the greatest, followed by ISO and CON torque, respectively. With ECC torque being the highest torque produced, ISO torque was 13.5% less than ECC, and CON toque was 36% less than the ECC torque. In addition, for the

CON and ECC muscle actions the greatest torque was produced when the joint was at 125° (170 N) and 105° (232 N), respectively. It was concluded that that the differences in torque between the different muscle actions were similar to those found in previous studies which state that ECC muscle actions produce greater torque than ISO muscle actions, and ISO muscle actions produce greater torque than CON muscle actions.

3. Mode-specific Mechanisms of Fatigue

Baker et al. (2)

The purpose of this investigation was to examine the roles of metabolic and non-metabolic factors in human muscle fatigue caused by short duration (SDE) and long duration exercise (LDE) protocols. Thirteen males and four females (mean ± SE = 31 ± 1.4 years) volunteered to perform either short duration exercise (n = 6) or long duration exercise (n = 5) of the tibialis anterior. For the SDE protocol, a blood pressure cuff was placed around the thigh and inflated after which the subjects performed a sustained maximal ISO muscle action. The LDE protocol consisted of 15 – 20 minutes of non-ischemic intermittent maximal contractions to produce a gradual decline in force. After exercise and during recovery, potential mechanisms of fatigue were assessed using voluntary, twitch, and tetanic forces; intracellular metabolites; and electromyographic signals. The results showed that after SDE, fatigue was closely correlated with increased inorganic phosphate (Pi) and that both force and Pi recovered within five minutes after exercise. For the LDE, force recovered more slowly, with significant fatigue remaining beyond 15 minutes after exercise although recovery of Pi was not slowed. In addition, electromyographic signals were not affected by either protocol. The authors suggested

that fatigue from SDE may be caused by metabolic mechanisms (i.e. Pi), and that fatigue from LDE may be caused by additional mechanisms such as impaired activation.

Sahlin and Ren (40)

The purpose of this study was to examine the relationship between changes in muscle metabolites and the contraction capacity in humans. Sixteen subjects (mean ± SD = 29 years) volunteered to perform two successive ISO muscle actions of the leg extensors at 66% of the maximal voluntary contraction (MVC) force to fatigue. Muscle biopsies were taken from the quadriceps femoris muscle prior to and following the fatiguing muscle actions. The muscle content of high-energy phosphates and lactate were similar at fatigue after both contractions but glucose 6-phosphate decreased after the second contraction. During recovery, muscle lactate decreased and was 74 and 43% of the value at fatigue after 2 and 4 minutes, respectively. The authors concluded that 1) after a fatiguing ISO contraction, force is restored more rapidly than endurance, 2) force is not limited by a high H^+ concentration. It was suggested that the relationship between acidosis and the fatigue process may be explained by an H^+ - mediated inhibition of the ATP-generating processes.

Miller et al. (33)

The purpose of this study was to examine the physiologic and biochemical mechanisms of muscle fatigue. Nine subjects (range = 18 – 43 years) volunteered to perform maximal isometric contractions (MVC) of the thumb adductors for a period of 4 minutes. During the muscle fatigue exercises, the subjects were measured with nuclear magnetic resonance spectrometry. The authors reported that during muscle contraction,

maximum voluntary contraction force (MVC) decreased by 50% after the first minute of contraction and 90% after the fourth minute. pH decreased from 7.1 to 6.8 during the 1st minute of exercise and from 6.8 to 6.6 during the third minute of exercise. During the first minute pH decreased from 7.1 to 6.8, and from 6.8 to 6.4 in the third minute. Phosphocreatine (PCr) decreased to 30% that of the control in the first minute and down to 10% in the second minute where it remained throughout the completion of the exercise. In addition, inorganic phosphate (Pi) increased rapidly in the first two minutes of contraction, with a smaller increase during the last two minutes. ATP decreased to approximately 70% of control during the third and fourth minute. Changes in MVC, pH, and PCr were similar. After the fatiguing exercise, MVC had risen to 83% of the control after 10 minutes, and 93% after 15 minutes. Mean pH increased 50% at 3.3 minutes and returned to control values after about 14 minutes of recovery. Phosphocreatine rose to 50% of control in about 2.7 minutes of recovery and reached control levels at about 10 minutes following exercise. Inorganic phosphate was the quickest to recover at 50% of control after 1.8 minutes of recover and 100% of control after only 6.2 minutes of recovery. Adenosine diphosphate and AMP returned to normal levels after 5 minutes of recovery. The authors concluded that the recovery of maximum force (15 – 20 minutes following exercise) correlated well with the changes in pH and PCr.

Crenshaw et al. (16)

The purpose of this investigation was to describe intramuscular pressure (IMP) response patterns of the vastus lateralis muscle during 100 repeated maximal isokinetic leg extensions. Four males and two females (range = 23 – 38 years) volunteered to perform 100 CON isokinetic muscle actions of the right leg extensors at a velocity of

$90°\cdot s^{-1}$ during simultaneous recording of torque, EMG, and IMP of the vastus lateralis. A myopress catheter was used to measure IMP and a Kin-Com isokinetic dynamometer was used to measure torque. The authors reported that mean IMP increased from 6.0 mmHg for the first muscle action to 14 mmHg for the 100th muscle action. It was suggested that a common factor occurring during the fatiguing process involves changes in IMP.

4. Patterns of Response for Intermittent ISO Fatigue

Burnley et al. (9)

The purpose of this study was to determine if critical torque could be estimated from the torque measured at the end of a series of maximal voluntary contractions in the right quadriceps. Eight men (mean ± SD = 29 ± 6 years) volunteered to visit the laboratory on eight occasions within a three week time frame. Following familiarization, subjects performed two tests of 60 intermittent isometric maximal voluntary contractions (MVC) (3 s contraction, 2 s rest), and five tests of intermittent isometric contractions at 35-60% MVC to failure on a Biodex System 3 isokinetic dynamometer. Critical torque was measured using linear regression of the torque impulse and contraction time during the submaximal tests. End-test torque during the MVC's was calculated from the mean of the last six contractions of the test. The end test torque during the MVC's was not significantly different from the critical torque. In addition, the percent decline during the MVC's was 70%. The plateau in torque that occurred at about the 30th repetition during the intermittent maximal contractions closely approximated the critical torque measured using submaximal contractions performed to failure. The authors concluded that 60

isometric MVC's of the quadriceps resulted in a decline in voluntary torque until a plateau was a viable means of estimating critical torque.

Allman and Rice (1)

The purpose of this investigation was to compare the ratings of perceived exertion (RPE) of young and old men during intermittent voluntary isometric contractions of the elbow flexors. Six young men (mean ± SD = 25 ± 2.4 years) and six old men (age = 84 ± 2.4 years) volunteered to perform a fatigue protocol which consisted of a continuous pattern of intermittent isometric contractions (3 seconds contraction, 2 seconds rest) of the forearm flexors at a target force of 60% maximal isometric contraction (MVC) using a strain gauge until the target force could no longer be achieved. Following every tenth target contraction a three second contraction at 60% target force was conducted, followed by 2 seconds rest, then a three second MVC. RPE were recorded during every sixth target contraction, and again during the last contraction. The authors reported that the MVC force for the old men was 36% less than that of the young men (345 N versus 221 N). There were no age differences in the average duration of the fatigue protocol (4.0 min young, 4.0 min old) or the remaining percentage of MVC force from the beginning of the fatigue session (81% young, 80% old), and at the end (56% young, 57% old). In addition, the old men reported greater RPE values than the young men during the initial stage of the fatigue protocols. There was no significant difference, in RPE between the young men and the old men at the other stages of the fatigue protocol. Both groups demonstrated a 40% reduction in the relative MVC force at the end of the fatigue protocol. The authors concluded that the old men were able to exert themselves to the same relative extent of muscle fatigue as the young men.

Callahan et al. (11)

The purpose of this investigation was to test the hypothesis that older adults who were matched to young adults with similar physical activity levels would (1) fatigue less during isometric leg extensor muscle actions, but (2) would show similar fatigue during dynamic leg extensions performed at $120°\cdot s^{-1}$. Sixteen young (mean ± SD: = 26.1 ± 0.9 years) and sixteen older (mean ± SD = 70.9 ± 1.1 years) individuals volunteered to visit the laboratory on two separate occasions. The fatiguing protocol consisted of baseline torque measurements before and after the protocol of 3-5 maximal voluntary isometric contractions followed by a series of three concentric isokinetic muscle actions at $120°\cdot s^{-1}$ of the leg extensors using a Biodex 3 isokinetic dynamometer. Following the baseline tests the subjects performed either a CON or ISO fatigue protocol. During the CON fatigue protocol, subjects performed four minutes of leg extensions at $120°\cdot s^{-1}$. During the ISO fatigue protocol, subjects performed four minutes of intermittent MVIC's with five seconds contraction and 5 seconds rest. Electrically stimulated contractions were used to evaluate central activation during both fatigue protocols. The authors reported that the older subjects produced significantly less torque during the MVIC and maximal CON muscle actions than the young subjects. The older group maintained a higher percentage of baseline maximum voluntary contraction torque than the young subjects during isometric contractions (Mean: 71% and 57%, respectively). There was no difference, however, between age groups in torque maintenance during dynamic contractions (43% and 44%, respectively.

Stackhouse et al. (44)

The purpose of this investigation was to examine the ability of young and elderly people to activate their quadriceps femoris muscles voluntarily under both fatigued and non-fatigued conditions to determine the effect of central activation failure on age-related loss of force. Eleven young men and women (mean ± SD = 22.67 ± 4.1 years), and 17 elderly men and women (mean ± SD = 71.5 ± 5.8 years) volunteered for this study. Central activation was based on the change in force produced by a 100-Hz, 12-pulse electrical train that was delivered during a three to five second maximal ISO contraction of the quadriceps femoris muscle group. Following the central activation assessment, subjects performed 25 MVC's (5 second contraction with 2 seconds of rest) to fatigue the muscle of the leg extensors using a Kin-Com isokinetic dynamometer. The authors reported that during rest, the younger subjects had higher central activation ratio's than the older subjects (mean ± SD: central activation ratio = 0.98 ± 0.03 and 0.94 ± 0.07, respectively). In a fatigued state the difference between the younger and older subjects became even greater (central activation ratio = 0.90 ± 0.10 and 0.74 ± 0.19, respectively). The elderly subjects demonstrated a larger decrease in normalized peak force than the young subjects during the first eight contractions. By the end of the test, however, both groups produced similar declines in normalized peak force. The authors suggested that some part of the age-related difference in strength may be attributed to failure of central activation in both the fatigued and non-fatigued states.

CHAPTER III

METHODS

Subjects

Ten female subjects (mean age ± SD = 22.7 ± 2.6 years; body weight = 60.4 ± 7.5 kg; height = 169.3 ± 6.2 cm) and ten male subjects (mean age ± SD = 21.9 ± 2.3 years; body weight = 87 ± 17.2 kg; height = 185.2 ± 10.7 cm) volunteered to participate in this investigation. Each subject visited the laboratory on three occasions. During the first visit, the subjects were asked to complete a health history questionnaire and sign an informed consent document. The subjects had no known cardiovascular, pulmonary, metabolic, muscular and/or coronary heart disease, or regularly used prescription medication. The second consisted of the orientation session, during which the complete testing and fatiguing protocol was performed, but no data were collected. The third session consisted of the testing and fatiguing protocol and data were collected. All subjects were instructed to avoid exercise for 48 hours prior to the second and third visits. This study was approved by the University Institutional Review Board for Human Subjects.

Orientation and Data Collection Sessions

During the orientation (visit 2) and data collection (visit 3) sessions, the subjects participated in the following study protocol.

Testing and Fatiguing Protocols

Warm-up

The subjects were positioned in accordance with the Cybex 6000 owner's manual (Cybex 6000 owner's manual) to perform forearm flexion muscle actions of their dominant (based on throwing preference) arm. Prior to the assessment of PT, the subjects performed a warm-up of three CON isokinetic and three ECC isokinetic muscle actions at $30°\cdot s^{-1}$, as well as three, 3-s MVIC muscle actions at an angle of 115° between the arm and forearm. The velocity of $30°\cdot s^{-1}$ for the CON and ECC isokinetic muscle actions was chosen due to the torque similarities to ISO muscle actions (3). The subjects were instructed to provide an effort corresponding to approximately 50% of their maximum during each muscle action. The warm-up was followed by a 120-s rest period.

Pre-test and Post-test

Following the warm-up, CON isokinetic, ECC isokinetic, and MVIC PT values were measured. For the determination of PT, subjects performed three CON isokinetic and three ECC isokinetic muscle actions at $30°\cdot s^{-1}$, and three, 3-s MVIC's at 115° between the arm and forearm (180° between the arm and forearm being full extension). The order of CON isokinetic, ECC isokinetic and MVIC muscle actions was randomized prior to the subject's arrival and the same order was used for both the pre-test and post-test. Each isokinetic muscle action was followed by a 3-s passive forearm extension or flexion movement (during the CON isokinetic or ECC isokinetic muscle actions, respectively) or 3-s rest (during the MVIC muscle actions). The repetitions which

produced the highest PT for each of the three muscle actions (CON, ECC, and MVIC) from the pre-tests and post-tests were used as representative scores for each subject.

Fatiguing Workbout

The fatiguing workbout immediately followed the pre-test measures of isokinetic and MVIC PT, and consisted of 50 repeated, maximal intermittent ISO muscle actions of the forearm flexors at an angle of 115° between the arm and the forearm. Each maximal 3-s ISO muscle action was followed by 3-s rest.

Reliability

Previous test-retest reliability from our laboratory for CON isokinetic and MVIC (at a joint angle of 115°) PT of the forearm flexors indicated that, for subjects measured 48 hours apart, the intraclass correlation coefficients (R) ranged from 0.87-0.93 (CON), and 0.99 (MVIC), with no significant differences between mean values for test vs. retest at velocities ranging from 30 to $300°\cdot s^{-1}$. In addition, Griffin et al. (22) reported that for ECC isokinetic PT of the forearm flexors at $30°\cdot s^{-1}$ the intraclass correlation coefficient (R) for test vs. retest was 0.80.

Statistical Analyses

The data were analyzed using a two (pre-test vs. post-test) x three (CON vs. ECC vs. MVIC PT) repeated measures ANOVA. Follow-up analyses included one-way repeated measures ANOVAs and/or paired *t* tests. An alpha of $P<0.05$ was considered statistically significant for all comparisons. The relationship for torque versus repetition number during the 50 fatiguing, maximal intermittent ISO muscle actions was examined

using polynomial regression analyses (linear, quadratic, and cubic; SPSS software program, V. 20.0 IBM SPSS Inc., Chicago, Illinois, USA). The statistical significance ($P<0.05$) for the increment in the proportion of the variance that was accounted for by a higher degree polynomial was determined using the following F-test.

$$F = \frac{(R_2^2 - R_1^2) / (K_2 - K_1)}{(1 - R_2^2) / (n - K_2 - 1)}$$

Where n is the number of data points, R_2^2 is the larger R^2, R_1^2 is the smaller R^2, K_2 is the number of predictions from the larger R^2, and K_1 is the number of predictions from the smaller R^2.

CHAPTER IV

ANALYSIS OF DATA

Results

The results of the 2 x 3 repeated measures ANOVA indicated no significant interaction ($P>0.05$; partial $\eta^2 = 0.17$) (Figure 1). There were, however, significant main effects for time ($P<0.05$; partial $\eta^2 = 0.78$) and type of muscle action ($P<0.05$; partial $\eta^2 = 0.56$). The follow-up paired t-tests for the marginal means for time (collapsed across type of muscle action) indicated that the pre-test torque (mean ± SD of CON, ECC, and ISO = 59.03 ± 27.60 Nm) was significantly greater than the post-test (mean = 40.82 ± 20.17 Nm) (Figure 1). In addition, the marginal means for the types of muscle actions (collapsed across time) indicated significant differences among the types of muscle action (ECC = 61.1 ± 30.9 Nm > ISO = 48.8 ± 22.9 Nm > CON = 39.9 ± 31.7 Nm). The mean % declines in torque for pre-test versus post-test were 31 ± 11, 28 ± 12, and 31 ± 9%, for the CON, ECC, and ISO muscle actions, respectively (Table 1). The results of the polynomial regression analyses indicated that 40% of the subjects (n = 8) demonstrated quadratic relationships ($R^2 = 0.52 – 0.95$), 40% (n = 8) demonstrated cubic relationships ($R^2 = 0.24 – 0.86$), and 15% (n = 3) demonstrated a linear ($r^2 = 0.33 – 0.62$) relationships, between torque and repetition number. There was no change, however, in torque versus repetition number for 5% (n = 1) of the subjects ($r^2 = 0.02$). In addition, the composite relationship between torque and repetition number was quadratic ($R^2 = 0.97$) (Figure 2).

Discussion

In the present investigation, there was a quadratic pattern ($R^2 = 0.97$) for the composite torque versus repetition number relationship (Figure 2) across the 50 maximal, intermittent ISO forearm flexion muscle actions. While no other investigations have characterized the fatigue-related patterns for intermittent ISO torque of the forearm flexors, Camic et al. (13) reported a linear ($r^2 = 0.95$) relationship for a fatiguing workbout of 30 maximal, intermittent ISO leg extension muscle actions. The difference between the fatigue-related patterns in the current study (quadratic), and that of Camic et al. (13) (linear), was likely due to a difference in the number of repetitions (50 vs. 30) performed during the fatiguing workbouts. For example, the pattern of responses for the composite torque versus repetition number relationship in the present study involved a curvilinear decrease in torque across the repeated muscle actions that reached a plateau after approximately 35 - 40 repetitions. Similar plateaus in torque have been reported (30-42 repetitions) in previous investigations of CON fatigue in the forearm flexors and leg extensors (16, 21, 27, 38). Thus, it is likely that the 30 repetitions used by Camic et al. (13) were not sufficient to elicit the plateau in torque production during the fatiguing workbout. Furthermore, it has been suggested (16) that the biphasic changes in torque during a fatiguing workbout can be characterized as a fatigue phase (initial curvilinear decline in torque) followed by a stable endurance phase (plateau in torque). The initial curvilinear decline in torque during a fatiguing workbout has been attributed to the increasing fatigue of type IIB muscle fibers, while the subsequent plateau phase reflects the torque produced from the other fiber types (16). Furthermore, Gerdle et al. (21), supported this hypothesis by showing a negative correlation between the type IIB muscle

fiber percentage and the plateau in torque across repetitions during a fatiguing workbout. Thus, the quadratic pattern ($R^2 = 0.97$) of responses in the present study showed a rapid decline in torque due to the fatiguing of the type IIB muscle fibers, followed by a plateau in torque due to the contribution of the other muscle fiber types.

The individual patterns of responses for the torque versus repetition number relationships in the present study showed a great deal of intersubject variability. For example, 16 subjects showed quadratic (n = 8) or cubic (n = 8) relationships, while 4 subjects showed linear relationships. In addition, one subject showed no decline in torque across the 50 repetitions. Typically, torque-related patterns of responses during fatiguing workbouts show a curvilinear decline, followed by a plateau in torque (4, 16, 18, 28, 38). In addition, the lowest torque values during a fatiguing workbout have been reported to occur during the last five repetitions (4, 13, 16, 18, 28, 38). More than half (n = 11) of the individual patterns of responses in the present study, however, showed increases in torque during the last five repetitions of the fatiguing workbouts. The increases in torque production at the end of the workbout may have been due to the end spurt phenomenon (14). Noakes and St Clair Gibson (36) stated that "…the end spurt phenomenon exists in all forms of human endeavor in which the duration of exercise is known before the activity commences so that a pacing strategy can be adopted" (p. 30). Thus, it is possible that, because the subjects knew the number of repetitions in the workbout, a pacing strategy was adopted. The adoption of a pacing strategy would have allowed some of the subjects (n = 11) to increase their torque during the last few repetitions of the fatiguing workbout. The intersubject variability shown in the current study gives greater insight

into the torque-related responses during fatiguing workbouts and suggest the importance of reporting such values in future investigations.

The 29% decline in intermittent ISO torque (difference between the highest and lowest torque values during the fatiguing workbout) as a result of the fatiguing workbout in the present study was greater than the 23% decline in intermittent ISO torque of the leg extensors reported by Camic et al. (12), but less than the 50% and 70% declines in CON torque of the forearm flexors reported by Beck et al. (4) and Linnamo et al. (30), respectively. The current findings, together with those of previous investigations (4, 13, 30) suggested that the difference in the velocities of the fatiguing muscle actions (0 - $180^{o}\cdot s^{-1}$), the number of repetitions (30 to 100), and the muscle groups tested (forearm flexors vs. leg extensors) affected the differences in the percent declines among studies (23 – 70%). Motzkin et al. (34) reported that PT decreased more rapidly for a fatiguing maximal, CON isokinetic test than for a maximal, ISO test. Therefore the differences in percent declines between the present study (29%), and those reported by Beck et al. (4) and Linnamo et al. (30) (50 and 70%, respectively) may have been due to the differences between the velocities ($0^{o}\cdot s^{-1}$ versus $180^{o}\cdot s^{-1}$, and 115 $^{o}\cdot s^{-1}$, respectively) used for the fatiguing workbouts. In contrast, it is possible that the difference between the 29% decline in the present study and the 23% decline reported by Camic et al. (12) was due to both, the differences in the number of repetitions performed during the fatiguing workbouts (50 versus 30), and the muscle groups used (forearm flexors versus leg extensors). For example, the absence of a biphasic change (i.e. rapid initial decline, followed by a plateau) in torque during the fatiguing workbout of Camic et al. (12), suggested that the stable endurance phase (i.e. plateau), which has been reported to occur

in previous investigations (16, 21, 27, 38), was not achieved. Therefore, it is possible that the 23% decline reported by Camic et al. (12) could have been greater and, thus, more similar to the 29% decline of the present study, with the addition of 20 repetitions to the fatiguing protocol. In addition, Beck et al. (5) suggested that the selection of the muscle groups used for testing may be more critical than the exercise protocol when comparing the effects of fatiguing workbouts. Therefore, the different percent declines between the present study and Camic et al. (12) could have been due to the heterogeneous fiber type distribution patterns between the forearm flexor (% type I: biceps brachii = 38–42%, brachioradialis = 29.5%), and the leg extensor muscle groups (% type I: leg extensors = 52%) (8, 24, 39). The greater proportion of type II muscle fibers in the forearm flexors suggests that this muscle group is more susceptible to fatigue than the leg extensors. Therefore, it is possible that this difference in fiber type distribution patterns between the two muscle groups (forearm flexors and leg extensors), partially contributed to the greater percent decline in the forearm flexors for the present study than the percent decline reported by Camic et al. (12) in leg extensors.

The results of the present study indicated that torque (measured pretest and posttest) declined by a mean of 31% for the CON, ECC, and ISO muscle actions. Camic et al. (12), however, reported a 17% decline in the mean of CON, ECC, and ISO torque after 30 leg extension muscle actions. The difference between the pretest and posttest percent declines in the present study and that of Camic et al. (12), was likely due to a difference in the number of repetitions (50 vs. 30) during the fatiguing workbouts. The individual percent declines for CON, ECC, and ISO torque following the fatiguing workbout in the present study were 31%, 29%, and 31%, respectively. Furthermore, there

was no mode-specific effect for the three types of muscle actions (CON, ECC, and ISO) measured pre and posttest. The results of the present study are consistent with previous investigations (5, 13, 28) that also reported no mode-specific effects due to fatiguing CON or intermittent ISO workbouts. For example, Camic et al. (12) reported similar declines in torque for CON, ECC, and ISO muscle actions (22%, 17%, and 14%, respectively), following 30 maximal, intermittent isometric muscle actions of the leg extensors. Therefore, both the current findings and those reported by Camic et al. (12), suggest that the same mechanism of fatigue may be responsible for declines in CON, ECC, and ISO torque following a fatiguing intermittent ISO workbout.

The physiological mechanisms responsible for decreases in PT during ISO muscle actions have been attributed to increased intramuscular pressure and occlusion of the vascular beds during contraction, leading to a restriction in blood flow (19). Crenshaw et al. (16) showed that these events create a greater diffusion distance between capillaries and muscle fibers, thus initiating the onset of fatigue. Simultaneously, accumulation of metabolic byproducts (i.e. ammonia, hydrogen ions, potassium, inorganic phosphate) from muscle contraction occurs within the muscle (19). Intermittent isometric muscle actions, however, allow for high muscle blood flow during the resting phase, which has been shown to attenuate fatigue by supplying the muscle with substrates for maintenance of homeostasis, removal of metabolites and heat, and by flushing K^+ away from the interstitial space (43). Future studies should examine each of these parameters to specifically identify which may be responsible for the fatigue-induced decline in torque following repeated intermittent ISO muscle actions.

In conclusion, there was a quadratic pattern for the composite torque versus repetition number relationship in the present study. For the individual relationships, however, there were quadratic (n = 8), cubic (n = 8) and linear (n = 3) patterns of responses. In addition, there was no change in the torque-related pattern of responses for one of the subjects. Eight of the subjects showed increases in torque during the last five repetitions during the fatiguing protocol. The mean percent declines in CON, ECC, and ISO torque as a result of the 50 intermittent ISO forearm flexion muscle actions were 31%, 29%, and 31%, respectively. In addition, there were no differences between the mean percent declines among the three types of muscle actions (CON, ECC, and ISO). These findings suggested that the intermittent ISO fatiguing workbout may have resulted in mechanisms of fatigue that caused the similar declines in torque for the CON, ECC, and ISO muscle actions.

CHAPTER VI

SUMMARY

Statement of Purpose

The purpose of the present study was to determine the effects of 50 maximal, intermittent ISO muscle actions of the forearm flexors on CON isokinetic, ECC isokinetic, and ISO PT.

Procedures for Collection of Data

20 adults [ten men (mean age ± SD = 21.9 ± 2.3 years) and ten women (mean ± SD age = 21.9 ± 2.3 years)] volunteered to perform 50 consecutive maximal, intermittent ISO forearm flexion muscle actions. Before and after the fatiguing workbouts, peak torque (PT) was measured (randomly ordered) for CON at $30^{o}\cdot s^{-1}$, ECC $30^{o}\cdot s^{-1}$, and ISO muscle actions.

Analysis

The effect of the fatiguing workbout was measured using a 2 (pre-test vs. post-test) x 3 (CON vs. ECC vs. MVIC PT) repeated measures ANOVA. Follow-up analyses included one-way repeated measures ANOVAs and/or paired *t* tests. The relationship for torque versus repetition number during the fatiguing workbout was measured using polynomial regression analyses.

Findings

Mode-specific effect

The 2 x 3 repeated measures ANOVA indicated no significant differences ($P>0.05$; partial $\eta^2 = 0.17$) for the declines in PT for the three muscle actions (CON, ECC, ISO) measured pre and post. There were, however, significant main effects for time ($P<0.05$; partial $\eta^2 = 0.78$) and type of muscle action ($P<0.05$; partial $\eta^2 = 0.56$). The follow-up paired t-tests for the marginal means for time (collapsed across type of muscle action) indicated that the pre-test torque (mean ± SD of CON, ECC, and ISO = 59.03 ± 27.60 Nm) was significantly greater than the post-test (mean = 40.82 ± 20.17 Nm). In addition, the marginal means for the types of muscle actions (collapsed across time) indicated significant differences among the types of muscle action (ECC = 61.1 ± 30.9 Nm > ISO = 48.8 ± 22.9 Nm > CON = 39.9 ± 31.7 Nm). The mean % declines in torque for pre-test versus post-test were 31 ± 11, 28 ± 12, and 31 ± 9%, for the CON, ECC, and ISO muscle actions, respectively.

Patterns of responses during the fatiguing workout

The polynomial regression analyses indicated that 40% of the subjects (n = 8) demonstrated quadratic relationships ($R^2 = 0.52 – 0.95$), 40% (n = 8) demonstrated cubic relationships ($R^2 = 0.24 – 0.86$), and 15% (n = 3) demonstrated a linear ($r^2 = 0.33 – 0.62$) relationships, between torque and repetition number. There was no change, however, in torque versus repetition number for 5% (n = 1) of the subjects ($r^2 = 0.02$). In addition, the composite relationship between torque and repetition number was quadratic ($R^2 = 0.97$).

Conclusions

The results of the present study showed that showed a quadratic pattern (R^2) for the composite torque versus repetition number relationship. The pattern of responses for the composite torque values showed a curvilinear decline in torque which plateaued after approximately 35 to 40 repetitions. The initial curvilinear decline in torque was likely due to the fatiguing of the type II muscle fibers, and the plateau in torque is reflective of torque production from mainly type I muscle fibers. In addition, there was a 29% decline in torque during the maximal, intermittent ISO fatiguing workbout in the present study.

For the individual patterns of responses for the torque versus repetition number relationships in the present study, 8 subjects showed quadratic, 8 subjects showed cubic, and 4 subjects showed linear. In addition, one subject showed no decline in torque across the 50 repetitions. Furthermore, 11 of the subjects showed an increase in torque during the last five repetitions of the fatigue protocol. This increase in torque at the end was attributed to the end spurt phenomenon. It was hypothesized that because the subjects experienced the fatigue protocol several days prior, a pacing strategy was adopted. The variability in the individual patterns of responses suggests the importance of reporting individual patterns of responses.

The present study showed that torque (measured pretest and posttest) declined by a mean of 31% for the CON, ECC, and ISO muscle actions as a result of the fatiguing protocol. In addition, the individual percent declines for CON, ECC, and ISO torque following the fatiguing workbout were 31%, 29%, and 31% respectively. Furthermore, there was no significant time (PRE and POST) x muscle actions (CON, ECC, ISO)

interaction for the fatiguing workbout. Thus, there were no mode specific effects in the present study. These findings suggest that the three different types of muscle actions (CON, ECC, and ISO) respond similarly to the physiological mechanisms of fatigue caused by the 50 maximal, intermittent ISO fatiguing workbouts.

Figure 1. Mean (± SD) torque values for concentric at 30°·s^{-1}, eccentric at 30°·s^{-1}, and isometric muscle actions, as well as marginal means (concentric, eccentric, and isometric), prior to (pre-test) and following (post-test) the 50 maximal intermittent, isometric forearm flexion muscle actions.

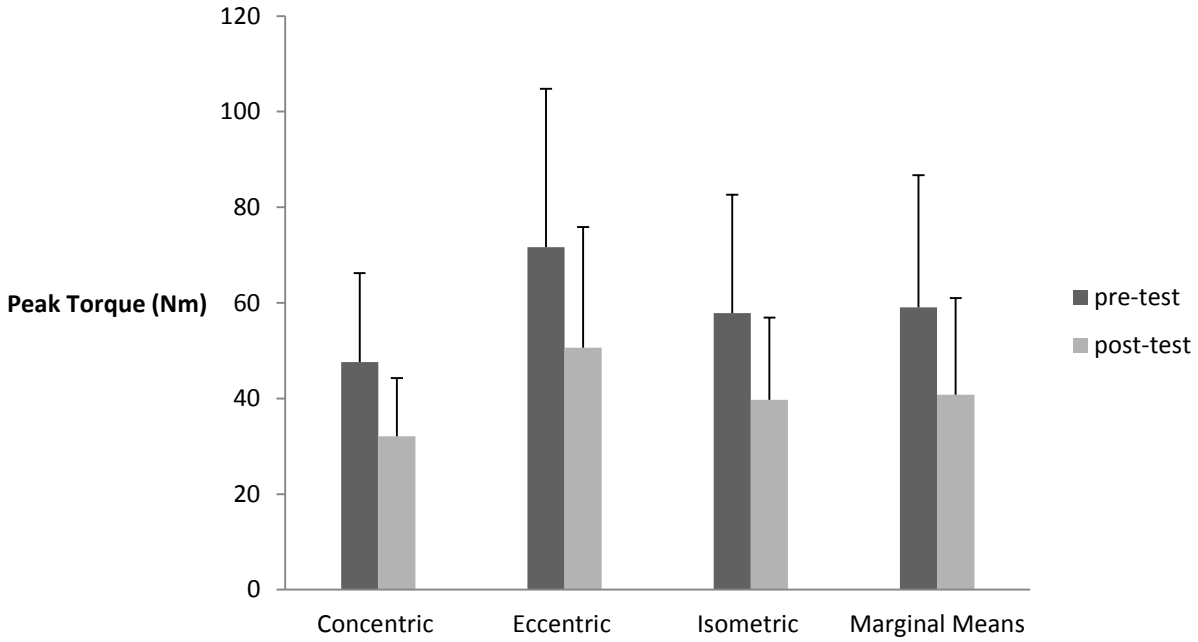

Figure 2. Composite pattern of response during the intermittent, isometric fatiguing protocol (n = 20).

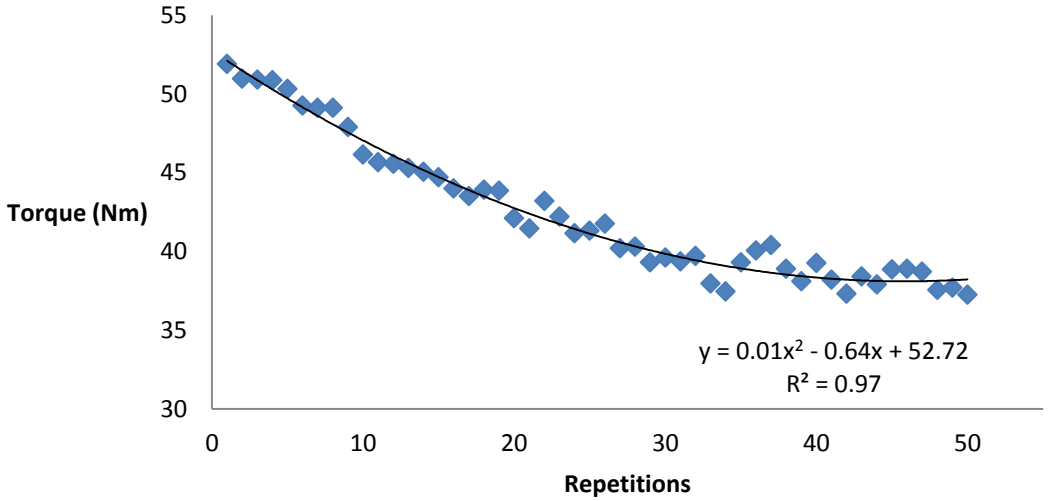

Table 1. Individual % declines for concentric ($30°\cdot s^{-1}$), eccentric ($30°\cdot s^{-1}$), and isometric torque following the fatiguing intermittent, isometric protocol.

Subject	Concentric % decline	Eccentric % decline	Isometric % decline
1	18.18	12.82	30.30
2	25.81	29.79	32.61
3	18.18	35.14	25.00
4	35.71	23.44	39.53
5	30.77	20.93	21.21
6	54.84	29.63	35.29
7	14.81	27.66	21.05
8	23.08	20.00	26.67
9	37.50	38.46	50.00
10	30.26	7.06	24.69
11	35.71	31.53	41.12
12	25.00	34.07	20.00
13	43.40	59.69	46.05
14	37.68	4.65	27.00
15	38.33	25.00	35.38
16	14.81	37.36	22.22
17	25.53	35.80	33.87
18	33.96	30.99	30.56
19	36.36	31.73	39.51
20	48.00	34.00	19.30
Mean	**31.40**	**28.49**	**31.07**
SD	**10.86**	**12.10**	**8.96**

Note: Percent declines were calculated (% decline = ((pre-test – post-test)/pre-test)*100) using the repetitions that produced the highest torque for each of the three muscle actions from the pre-tests and post-tests.

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APENDIX A

Glossary

CON concentric

ECC eccentric

ISO isometric

Nm neuton meters

APPENDIX B

Human Performance Laboratory
Center for Youth Fitness and Sports Research
Department of Nutrition and Health Sciences
110 Ruth Leverton Hall
University of Nebraska-Lincoln
Lincoln, NE 68583-0806

Director: Terry J. Housh, Ph.D.

Statement of Informed Consent

Title of Research Study

Mode-specific effects of fatigue on isokinetic and isometric strength of the forearm flexor

Invitation to Participate

You are invited to participate in this research study. The following is provided in order to help you make an informed decision whether or not to participate. If you have any questions, please do not hesitate to ask.

Basis for Subject Selection

You were selected as a potential volunteer because you are between the ages of 19 and 29 years and are in good health. If you wish to participate you must fill out a health history questionnaire. You may be prevented from participating in this research study if there are indications from the questionnaire that you may have health risks. Such indications include symptoms suggestive of chest pain, breathing difficulties, irregular heartbeat, kidney or liver problems, and/or high blood pressure or cholesterol. Muscle and/or skeletal problems including previous or current ankle, knee, and/or hip injuries may also preclude you from participation in this study. If you have no muscle or skeletal problems or disorders that will prevent you from engaging in physical activity, you will be asked to perform the tests described below. Overall, there are numerous health-related issues that may preclude you from participation in this study which will be determined through the health history questionnaire.

Purpose of the Study

The present study is designed to examine the strength of your arm muscle (biceps brachii) after fatiguing muscular contractions.

Explanation of Procedures

You will be asked to visit the Human Performance Laboratory located in Mabel Lee Hall (Room 141) on the UN-L campus on three separate occasions. The first laboratory visit will consist of you filling out a health history questionnaire and scheduling your next two visits.

The exercise tests described below will be scheduled at your convenience and conducted in the Human Performance Laboratory. The second and third visits will consist of the same procedure (described below). The second visit, however, will be treated as an orientation session to familiarize you with the testing procedures and equipment to be used during the study. During these laboratory visits you will have the option of pedaling on a stationary bicycle for five minutes as a warm up. Following the bicycle warm-up, you will be asked to perform a warm-up (following correct positioning on the machine that will measure your biceps brachii muscle strength) consisting of several light biceps curls. Following the warm-up and a rest period of two minutes, you will be asked to perform 3 different types of biceps curls (the three types of biceps curls include: curling the weight upwards, bringing the weight downwards and pulling up with your bicep as hard as possible against an object that does not move). These three types of biceps curls will be randomly ordered prior to your arrival to the laboratory. During each maximal biceps curl, you will be encouraged to produce as much force as possible. You will then be asked to perform a fatigue protocol consisting of 50 static biceps curls (you will be pulling up as hard as possible with your biceps brachii muscle against an object that does not move for 3 seconds, following each repetition, you will relax your biceps brachii for 3 seconds). After you complete the fatigue protocol (50 maximum weight static biceps curls), you will be asked to repeat the three different biceps curls (that is: curling the weight upwards, bringing the weight downwards and pulling up with your bicep as hard as possible against an object that does not move) that you performed before the fatigue protocol in the same order.

Total Time Commitment

The total time commitment for this study will be approximately 1.5 hours with each session lasting 30 minutes.

Potential Risks and Discomforts

The following are the potential risks and discomforts you may experience during this study:

- Strength Tests – Performing maximal strength tests may lead to muscle tears or soreness, dizziness, headache, acute elevation of blood pressure, heart attack, stroke, or sudden death. According to the American College of Sports Medicine, the absolute risk of sudden cardiac death during vigorous physical activity has been estimated at one per year for every 15,000 – 18,000 people.

Protection Against Risks

You also will be given instructions for special stretches which may aid in the elimination of any muscle soreness as a result of the tests. Throughout all the tests, you will be monitored by laboratory personnel trained in Cardiopulmonary Resuscitation (CPR). In addition, you will be asked repeatedly during the tests how you feel in relation to your ability to continue the test.

Potential Benefits to Subjects
Your main benefit from participating in this study may be feedback on your level of physical fitness. In addition, you may gain insight into your own fatigue process, an important component of health-related fitness.

Subject Compensation
You will receive a $16.66 stipend for each session you complete. For example, if you complete only session 1, you will receive $16.66 and if you complete all three sessions 1, 2 and 3 you will receive the full $50 stipend.

Potential Benefits to Society
Although there are no direct benefits by participating in this study, society may benefit from this research by having a better understanding of how to conduct scientifically-based exercise programs in sport, rehabilitative, and recreational settings.

In Case of Emergency Contact Procedures
In the event of a research-related injury, immediately contact one of the investigators listed at the end of this consent form.

Medical Care in Case of Injury
In the unlikely event that you should suffer an injury as a direct consequence of the research procedures described above, the acute medical care required to treat the injury can be provided at the University of Nebraska Health Center from the hours of 8:00 a.m.–6:00 p.m. Monday through Friday, and 9:00 a.m.–12:30 p.m. Saturday (for urgent care needs only). For UNL and non-UNL students, the cost of such medical care will be the responsibility of the subject, whether at the University Health Center or at other local health care facilities. If the health center is unable to treat you, emergency care is available at local community health providers. In addition, in the case of an adverse event, you may be asked to sign a Private Health Information Authorization allowing access to your related medical documents for review by the Institutional Review Board and associated personnel.

Assurance of Confidentiality
Any information obtained from this study which could identify you will be kept strictly confidential. The primary investigator will ask for your social security number which will be used for payment purposes only. Your social security number will be kept in a locked filing cabinet in the office (Room 141 Mabel Lee Hall) of the primary investigator. Once your payment has been sent out, the document containing your social security number will be destroyed promptly (within one week of you receiving the payment). The information obtained from your participation may be published in scientific journals or presented at scientific meetings. Your identity will be kept strictly confidential. All data collected as a result of your participation will be kept in a locked cabinet in the office of the primary investigator (Room 141 Mabel Lee Hall). Your data will receive an identifying number and only the investigators will be able to identify you from your data. Your data will be compiled and only group data will be used for dissemination without

identifying your name. For the purposes of future reference, your data will be stored for a minimum of 15 years.

Rights of Research Subjects

You may ask any questions concerning this research and have those questions answered before agreeing to participate in or during the study. Or you may call the investigator, Robert Lewis, at any time, office phone, (402) 472-2690, or after hours (858) 213-9025. You may also contact Dr. Terry Housh at his office phone, (402) 472-1160, or after hours (402) 477-6573. Please contact the investigator:

- if you want to voice concerns or complaints about the research
- in the event of a research related injury.

Please contact the University of Nebraska-Lincoln Institutional Review Board at (402) 472-6965 for the following reasons:

- you wish to talk to someone other than the research staff to obtain answers to questions about your rights as a research participant
- to voice concerns or complaints about the research
- to provide input concerning the research process
- in the event the study staff could not be reached.

Voluntary Participation Withdrawal

You are free to decide not to participate in this study, or to withdraw at any time without adversely affecting your relationship with the investigators or the University of Nebraska. Your decision will not result in any loss of benefits to which you are otherwise entitled.

You are voluntarily making a decision whether or not to participate in this research study. Your signature certifies that the content and meaning of the information on this consent form have been fully explained to you and that you have decided to participate having read and understood the information presented. Your signature also certifies that you have had all your questions answered to your satisfaction. If you think of any questions during this study, please contact the investigators. You will be given a copy of this consent form to keep.

_____ _____

Signature of Research Participant Date

_____
Printed name of Research Participant

My signature as witness certifies that the subject signed this consent form in my presence as his/her voluntary act and deed.

_____ _____
Signature of Investigator Date

Investigators:

Robert Lewis	work phone	(402) 472-2690
	home phone	(858) 213-9025
Terry Housh	work phone	(402) 472-1160
	home phone	(402) 477-6573

PRE-EXERCISE TESTING HEALTH STATUS QUESTIONNAIRE

Subject Number _____

In reference to weight, have you experienced: a gain____ a loss____ no change____ in the past year?

If a change, how many pounds?_____(lbs)

A. JOINT-MUSCLE STATUS (✓Check areas where you currently have problems)

Joint Areas Muscle Areas

( ) Wrists ( ) Arms

( ) Elbows ( ) Shoulders

( ) Shoulders ( ) Chest

( ) Upper Spine & Neck ( ) Upper Back & Neck

( ) Lower Spine ( ) Abdominal Regions

( ) Hips ( ) Lower Back

( ) Knees ( ) Buttocks

( ) Ankles ( ) Thighs

( ) Feet ( ) Lower Leg

( ) Other_____ ( ) Feet

( ) Other_____

B. HEALTH STATUS (✓Check if you previously had or currently have any of the following conditions)

( ) High Blood Pressure ( ) Acute Infection

( ) Heart Disease or Dysfunction ( ) Diabetes or Blood Sugar Level Abnormality

( ) Peripheral Circulatory Disorder ( ) Anemia

( ) Lung Disease or Dysfunction ( ) Hernias

( ) Arthritis or Gout ( ) Thyroid Dysfunction

( ) Edema ( ) Pancreas Dysfunction

( ) Epilepsy ( ) Liver Dysfunction

( ) Multiply Sclerosis ( ) Kidney Dysfunction

( ) High Blood Cholesterol or ( ) Phenylketonuria (PKU)

Triglyceride Levels ( ) Allergic Reactions to Medication

( ) Loss of Consciousness please describe_____

( ) Others That You Feel We Should Know ( ) Allergic Reactions to Any Other Substance

About_____ please describe_____

( ) Pregnant78

C. PHYSICAL EXAMINATION HISTORY

Approximate date of your last physical examination_____

Physical problems noted at that time_____

Has a physician ever made any recommendations relative to limiting your level of physical exertion? _____YES _____NO

If YES, what limitations were recommended?_____

_____

Have you ever had an abnormal resting electrocardiogram (ECG)? _____YES_____NO

D. CURRENT MEDICATION USAGE (List the drug name and the condition being managed)

MEDICATION CONDITION

_____ _____

_____ _____

_____ _____

E. PHYSICAL PERCEPTIONS (Indicate any unusual sensations or perceptions. ✓Check if you have recently experienced any of the following during or soon after *physical activity* (PA); or during *sedentary periods* (SED))

PA SED PA SED

( ) ( ) Chest Pain ( ) ( ) Nausea

( ) ( ) Heart Palpitations "fast irregular heart beats" ( ) ( ) Light Headedness

( ) ( ) Unusually Rapid Breathing ( ) ( ) Loss of Consciousness

( ) ( ) Overheating ( ) ( ) Loss of Balance

( ) ( ) Muscle Cramping ( ) ( ) Loss of Coordination

( ) ( ) Muscle Pain ( ) ( ) Extreme Weakness

( ) ( ) Joint Pain ( ) ( ) Numbness

( ) ( ) Other_____ ( ) ( ) Mental Confusion

F. FAMILY HISTORY (✓Check if any of your blood relatives . . . parents, brothers, sisters, aunts, uncles, and/or grandparents . . . have or had any of the following)

( ) Heart Disease

( ) Heart Attacks or Strokes (prior to age 50)

( ) Elevated Blood Cholesterol or Triglyceride Levels

( ) High Blood Pressure

( ) Diabetes

( ) Sudden Death (other than accidental)

G. CURRENT HABITS (✓Check any of the following if they are characteristic of you current habits)

( ) Smoking. If so, how many per day?

( ) Regularly does manual garden or yard work

( ) Regularly goes for long walks

( ) Frequently rides a bicycle

( ) Frequently runs/jogs for exercise

( ) Regularly participates in a weight training exercise program

( ) Engages in a sports program more than once per week. If so, what does the program consist of?