NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

ISBN 0-315-56431-8

THE RELATIONSHIP BETWEEN BLOOD LACTATE AND FORCE PRODUCTION IN ELITE CROSS COUNTRY SKIERS

by
Mary B. Mackenzie, B. Sc.

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Kinanthropology

University of Ottawa
1988
Ottawa, Ontario

UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

DEDICATION

To my parents, for your support in all my endeavors.

ACKNOWLEDGEMENTS

Thanks must be directed first to Dr. Al Reed, for his patience, critical eye and insights.

Thanks also to Dr's Mainwood and Thoden for their time and valuable feedback.

A number of friends contributed significantly, not just in their support, but with much advice, technical assistance, and critical feedback; Pete Saar, Rick Chin, Eva Freisinger and Mike Egan. Many thanks also to Ryan Stark, for invaluable computer assistance.

Finally, to Ben, for being there in the final push.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Mackenzie, Mary, University of Ottawa, Master's thesis (Kinanthropology) 1988. The Relationship Between Force and Lactate Production in Elite Cross Country Skiers. The relationship between force and lactate production during a two minute intense exercise was investigated among elite male and female cross country skiers. Understanding the relationships between energy transduction, as indicated by blood lactate levels, and muscle force production, a sensitive fatigue reflector, may be integral to understanding the limitations to performance in a specific exercise situation.

Seventeen members of the Canadian National cross country ski team, nine males and eight females, performed a two minute maximal exercise on a training device and ergometer known as a rollerboard. Force values were continuously recorded as each athlete pulled his/her weight along a 21.5/26 degree angled ramp at a recorded cadence of one pull every 2.5 seconds. The forces were recorded using a strain gauge which was attached at one end to the ergometer and at the other to an Apple IIe computer. The changes in forces output during the two minutes provided a basis for calculating certain fatigue indicators.

Fingertip blood lactate sampling occurred at two and three minutes post exercise. The samples were immediately heamolyzed with a diluting

solution and then analyzed for blood lactate within five hours of collection using a Kontron Medical 640 lactate analyzer. The resulting data for both force and lactate were then analyzed statistically for the descriptive results, significance of difference between the male and female groups, and finally the correlational matrices were calculated for males and females independently, as well as for pooled data.

The results showed a highly aerobically fit group (mean age 21 years) with a significant difference in weight, peak force and maximal VO2 levels between males and females. Significant differences were also found in the correlations for the variables between the genders. A strong positive relationship was found between the peak and mean force values for both genders while several differences in correlations were observed for a number of force, fatigue and lactate variables. Different fatigue patterns both among and between the genders were observed; with two distinct patterns for the men and one general pattern for the women. The women showed non-traditional relationships between both strength and fatigue, and between fatigue and lactate production. As a result of these conclusions, a more cautious approach to generalizations about exercise induced force and lactate relationships for males and females is recommended.

I

THE PROBLEM

1.1 INTRODUCTION

The analysis of a movement task within athletic performance is a major focus of the sport sciences. Athletic performance is dependent upon several factors, including the structure and biochemical profile of skeletal muscle, the cardiovascular system, the mechanics of muscle and joint, and the structure and function of the nervous system. While it may not be practical, or even possible, to measure all of these factors in the analysis of a specific exercise, understanding the relationships among selected factors associated with the performance may provide a more complete picture of the exercise.

A task which is performed over a period of thirty to one hundred and twenty seconds requiring a high rate of force development and a high rate of energy output is generally associated with the anaerobic energy systems (Astrand and Rodahl, 1977; Gollnick, 1968; Karlsson, 1979; Jacobs, 1986). Anaerobic glycolysis supplies the majority of the energy necessary for work of this length and intensity via the resynthesis of ATP. This process results in the production of high levels of lactate; as high as 25-30 mM/l in muscle (Donaldson, 1983) or 17mM/l in blood (Hultman and Sahlin, 1980). Lactate production is reported to be proportional to the energy expenditure beyond the point of maximal aerobic

power (Gollnick, 1968; Margaria, 1968), and has been identified as a chief limiting factor to anaerobic performance (Gollnick and Hermanssen, 1974; Karlsson, 1979; MacDougall, 1975).

Agreement over the measurement and quantification of the anaerobic lactic system has not been universal. The use of the oxygen debt value obtained from the measurement of the recovery oxygen consumption above resting values, seen in many early studies, is not as accurate as might be desired. Some of the inaccuracies result from the fact that factors other than lactate may result in elevated oxygen consumption, and that some immeasurable quantity of lactate is oxidized during the exercise (Dainty, 1971; Saltin, 1986). Furthermore, the measurement of blood lactate may not give a true indication of the total amount of the lactate produced from anaerobic metabolism. However, the combination of the use of a direct measure of the amount and/or quality of work performed, together with physiological measures such as blood lactate has been more recently used as an indication of anaerobic lactic capacity (Fujitsuka et.al., 1982; Ohkuwa et.al., 1984; Thompson and Garvie, 1981; Thompson, 1981). There remain, however, many discrepancies in the literature regarding the precise measurement of anaerobic lactic fitness (Dainty, 1971; Saltin, 1986; Simoneau et.al., 1983).

Force production, studied by biomechanicians as a measure used to determine work and power output, is a measure traditionally used by exercise physiologists in the determination of anaerobic fitness, as in the Wingate, Katch, and De Bruyn-Prevost anaerobic lactic tests (Bar-Or, 1987; DeBruyn-Prevost, 1978; Katch and Weltman, 1979). In most movements, the important force production properties are:

1) the rate at which force is developed,

2) the amount of force developed,

3) how these force production characteristics vary with time.

These variations in force production that occur over time are considered to reflect the degree of fatigue experienced.

When considering a specific sport movement task, an assessment of the ability to perform should recognize that every exercise situation is unique, having a specific pattern in its demands on such factors as anaerobic energy yield, neuromuscular function, specificity of muscle groups and range of motion used in the movement. The specific effects on the energy systems as a result of high performance training also need to be recognized. In a case study by Astrand (1984), an elite swimmer who was monitored over several test sessions attained the same maximal aerobic power when tested on a treadmill, yet the maximum attained when tested while swimming varied in accordance with the intensity of training and with competitive performance. This demonstrates a significant variation in results between testing modes as a result of the exercise situation. It also demonstrates significant variation within the individual as a response to training. While there are also significant genetic variations which may affect the values obtained on physiological testing, it is generally believed that training is a significant causal factor for these variations (Astrand, 1984; Bouchard et.al., 1982). Thus the specific pattern of each exercise situation and the differences in values found during different phases of training provide a rationale for the use of sport specific testing for accurate physiological assessment of athletes.

Muscular fatigue is defined as the failure to develop or maintain the required or expected force during muscular exercise (Edwards, 1982; Karlsson, 1980). This paper focuses on the degree and pattern of muscular fatigue in a specific exercise situation, as measured via changes in force production. There has been much research recently on the topic of fatigue (eg. International Symposium of the Biochemistry of Exercise,1983, C.I.B.A. Foundation Symposium - Human Muscle Fatigue, 1982). As a result of these and earlier investigations (Margaria, 1933; Merton, 1954; Meyerhof, 1920, etc.), it has been established that muscular fatigue is a complex phenomenon and that the identification of the factors leading to the impairment of performance depends upon the conditions under which exercise is conducted. The major contributors to force output have been identified and include; muscle fibre composition (i.e.fast twitch/slow twitch ratio), muscle structure (Hakkinen et.al., 1981; Komi 1983), neuromuscular transmission (Bigland-Ritchie, et.al., 1983; Edwards, 1983; Komi, 1980), the excitation-contraction coupling of electro-mechanical activation (Donaldson, 1983; Karlsson, 1979), and energy supply and/or energy transduction (Assmussen, 1974; Gollnick and Hermanssen, 1974; Jacobs, 1981; Karlsson, 1979; Komi, 1979). This study focuses on the latter; the dynamics of energy transduction applied to a sport specific exercise and reflected by changes in force production and by blood lactate values.

The impairment of energy transduction mechanisms has a profound effect on muscle force production. The importance of force production to cross country skiing is most appropriately connected to the bursts of short term, high intensity efforts required by the demands of terrain

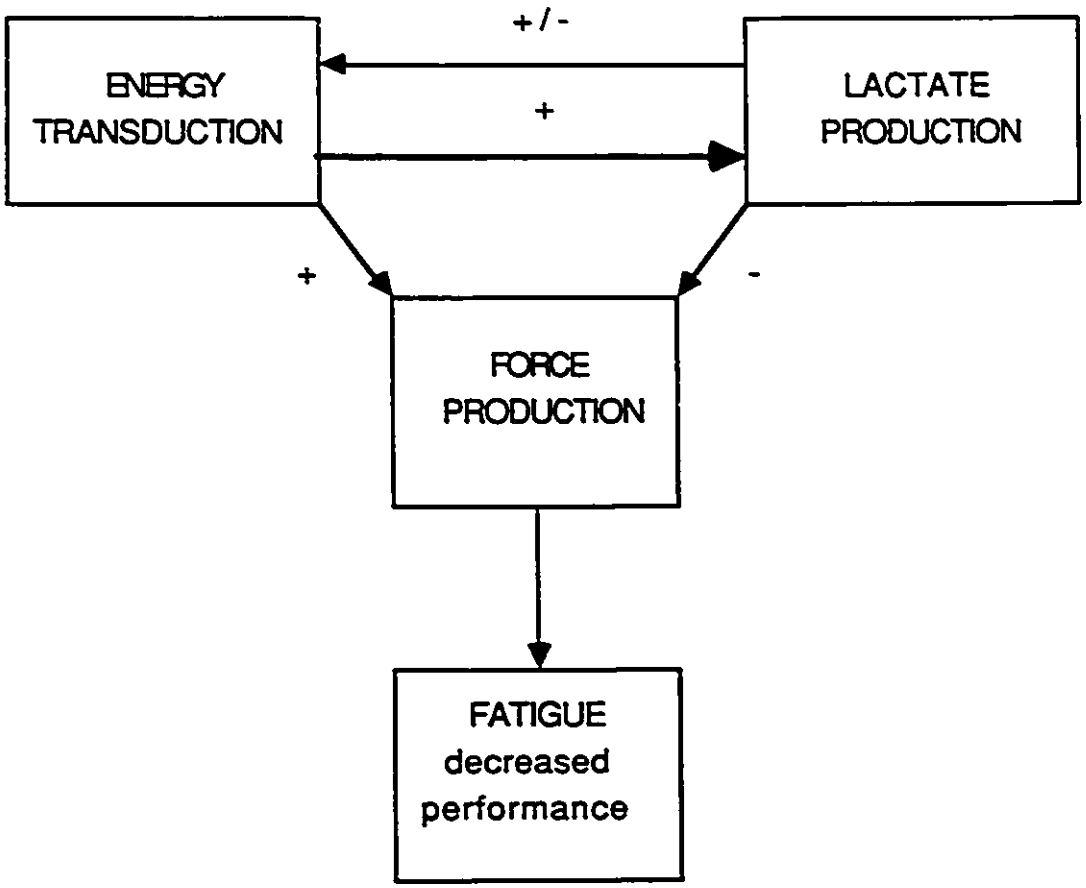
and/or strategy of a ski race. It is generally accepted (Caldwell, 1981; Hickson, 1980; Scheier, 1983) that cross country ski racing places large demands on the aerobic system, requiring the ability to work at a high anaerobic threshold level (Kindermann et.al., 1979), as well as the ability to produce sufficient energy via the anaerobic lactic system. The demand on the anaerobic lactic system has been suggested in part by the reporting of high heart rates (175-190 bpm) indicating high intensity levels during steep climbs and finishing sprints (Hickson, 1980).

In summary, the analysis of short term intense exercise should include measures which indicate the metabolic demands as well as some performance measure. This can be realized by measuring blood lactate and force output. Although significant advances have been made in identifying the contribution of the aerobic system (including high anaerobic threshold levels) to cross country ski racing (Christensen, 1950; Karlsson, 1971; Kindermann et.al., 1979; Rusko et.al., 1978; Saar, 1986), this does not give a complete picture of the energy demands required of the skier. While there is agreement that both the aerobic and anaerobic lactic systems are involved, the dynamics of the lactic system in cross country skiers have not yet been investigated (Bergh, 1980). Understanding the relationship of anaerobic lactic energy transduction, as indicated by high levels of blood lactate, to muscle force production, which is a sensitive reflector of fatigue (see figure 1, page 7) may be integral to understanding the limitations to performance in an exercise which requires maximal effort. A preferred method of investigating the above relationship is to analyze the force and lactate variables using movements similar to those in which the athlete is trained. Since cross

country ski performance is highly influenced by external and environmental conditions, it is impractical to test ski racers under truly sport specific conditions. Some compromise between sport specificity and the control and accuracy permitted under laboratory conditions must be made.

Since the delay or offsetting of muscle fatigue is a key to success in many sport performances, a greater understanding of the mechanisms of fatigue in an exercise which is reasonably close to the movements of the sport may ultimately lead to improved performance. As a result of the analysis of those physiological variables which are highly associated with the anaerobic lactic fatigue in an athletic group, it may be possible to contribute to the understanding of the role of this system, through the analysis of the interaction of force and blood lactate during an exercise which stresses the anaerobic lactic system.

Figure 1: The Relationship Between Force Production and Energy Transduction



1.2 STATEMENT OF THE PROBLEM

The purpose of this study was to investigate among elite male and female cross country skiers, force and peak post-exercise blood lactate generated during two minutes of exercise on a dry-land training device known as a rollerboard.

This study had three primary objectives:

1. To compare male and female cross country skiers on force and lactate variables generated during an intense short term exercise.

2. To identify any relationships between the force values and the post-exercise blood lactate.

3. To identify any relationships between the fatigue indicators as derived from the force production analysis and the post-exercise blood lactate.

A secondary objective was to investigate the relationships between the aerobic fitness level (as indicated by maximal VO2 values) and the force and lactate variables.

1.3 EXPERIMENTAL HYPOTHESIS

It was expected that significant relationships would be found between the force and blood lactate such that those athletes who could produce the highest levels of force would produce higher levels of lactate. It was also hypothesized that the post-exercise lactate levels would be positively correlated with an earlier occurance of fatigue as well as a greater degree of fatigue.

1.4 LIMITATIONS

There are a number of factors which cannot be controlled, including the amount and type of training of the athletes, the variations in technique in using the roller board, and the different environmental conditions in the laboratory as compared to 'on snow' conditions. The exercise itself is limited in the emphasis upon the anaerobic lactic system from its context within a largely aerobic performance. No attempt was made to assess the quantitative contribution of the aerobic and anaerobic systems. As well, blood lactate only was measured; no attempt was made to measure muscle lactate.

The accuracy of the rollerboard to double poling simulation is as yet unknown, although the testing device is commonly used for ski training and it was assumed that the athletes were well trained in its use. Also, the results of this study may only be applied to a very specific group of subjects - competitive cross country skiers.

1.5 ABBREVIATIONS

ALC — Anaerobic lactic capacity; the total energy transduction of the anaerobic lactic system.

ATP — Adenosine triphosphate

ADP — Adenosine diphosphate

AMP — Adenosine monophosphate

FT — Fast twitch; highly glycolytic muscle fibre.

ST — Slow twitch; highly oxidative muscle fibre.

NAD — Nicotinamide-adenine-dinucleotide; electron carrier and co-enzyme (NADH = reduced coenzyme).

IM — Intermediate; muscle fibre with characteristics intermediate between ST and FT fibres.

F-Peak — Peak force value recorded during the exercise; an indication force production capability.

F-Mean — Mean force calculated from the average of all (48) pulls during the exercise.

TDO — Time to drop-off, when force values are consistently lower than the lowest of the early peak values; an indication of how long fatigue can be resisted.

DO-Index — An index indicating the amount of fatigue in absolute terms.

It is defined as DO-Index = (a+b); where a = mean of force values recorded from 5 to 15 seconds, and b = mean of force values from 105 to 115 seconds.

M-Index An index of force maintenance, or the degree of fatigue resistance. It is defined as M-Index = B/A x 100; where A = mean of all recorded values prior to drop-off (TDO) and B = mean of all recorded values after drop-off.

II

THE REVIEW OF RELATED LITERATURE

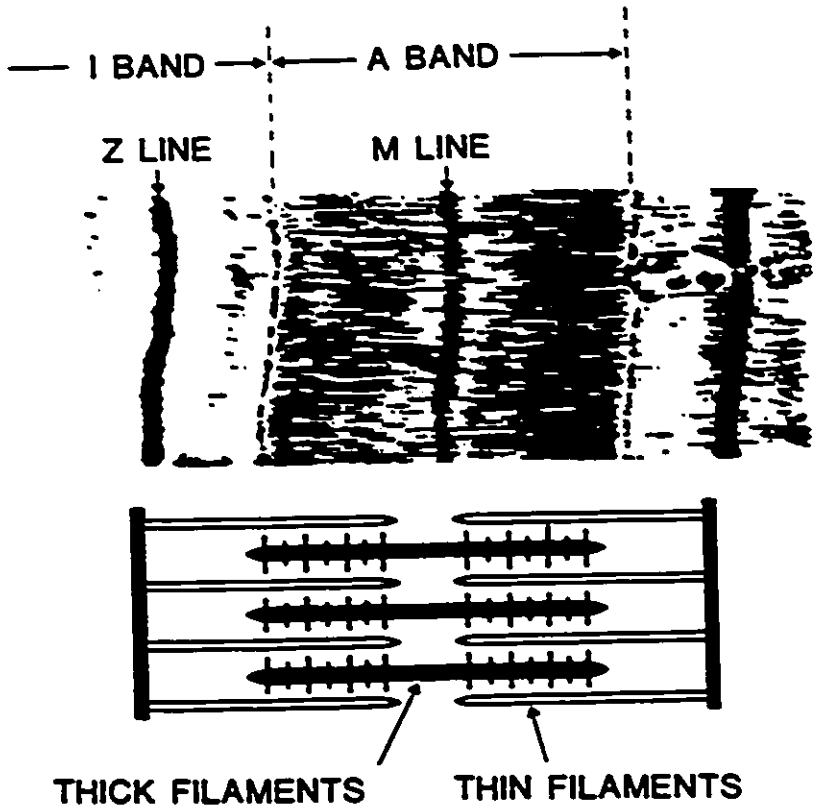
2.1 INTRODUCTION

The review of literature regarding force production and lactate production and the course of these variables over a two minute high intensity, ski specific exercise shall be presented in six sections. The first section shall outline the production of the muscle contraction and factors which influence it. The second shall deal with the energetics of force production in skeletal muscle, specifically relating to the anaerobic energy production. The third section shall deal with the decline in force production or muscular fatigue. Finally, the last three sections shall focus on fatigue during athletic performance, training effects on the anaerobic system and the relevance of anaerobic lactic energy production, with it's attendant muscle fatigue, to the sport of cross country skiing.

2.2 THE MUSCLE CONTRACTION

The current concept of muscle force production is based on the sliding filament theory of muscle contraction originally developed in the mid-1950's (Huxley, 1957). It has since been refined as increasingly more has become known about both the structure, and the enzymatic and ionic interactions occurring within the muscle cell.

Figure 2: The Sarcomere (from Woledge, Curtin and Homsher, 1985)



Although there are a number of different theories and some unanswered questions regarding the precise structure and behaviour of the sarcomere (the basic contractile unit-see previous page), there are enough facts to support the following basic proposal (Huxley, 1980 Pollack, 1983; Woledge, et.al., 1985). This theory is based on two established concepts of sliding filaments and crossbridges. This involves the sliding movement of thick filaments relative to thin filaments during contraction which is produced by crossbridges acting as more or less independent generators of force. The relative movements of these filaments cause the sarcomere to shorten and create tension. The process is generally separated into two parts; excitation and contraction. The following description represents a version of the most widely accepted theory.

2.2.1 Excitation

In the resting position, the formation of the actomyosin crossbridge is prevented by an inhibitory effect of the troponin-tropomyosin complex. However, when the motor neuron stimulates the muscle, the action potential depolarizes the cell membrane and allows the spread of the action potential inward via the transverse tubular (T) system. This alters the membrane permeability of the terminal cisternae of the sarcoplasmic reticulum (SR) so that Ca++ ions may be released from the SR into the fluid surrounding the contractile protein. The ions then become bound to the troponin of the thin filament (consisting of an actin-troponin-tropomyosin complex).

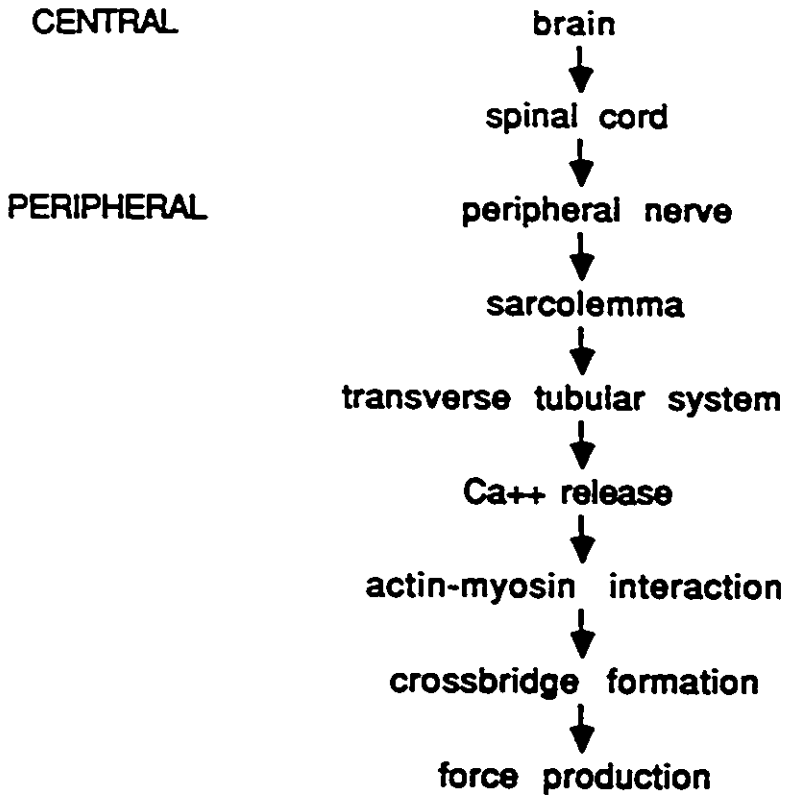
2.2.2 Contraction

The binding of Ca++ causes some conformational change (as yet un-identified) of the thin filament complex, removing the inhibition for interaction between the actin and myosin. The globular head of the myosin then moves out by virtue of a 'tail hinge' and attaches to the actin. The attached bridges undergo a structural-chemical transition so as to produce tension. The precise mechanism of this change is as yet unknown (Pollock, 1983). It is proposed that during shortening, the crossbridges break and re-attach further along the thin filament to allow movement much greater than the length of the individual crossbridge. This is known as crossbridge cycling. The force generated by the crossbridges tends to move the thin filament toward the centre of the sarcomere.

Fresh ATP is taken up by the myosin head, dissociating the actin from the myosin, and two Ca++ are resequestered back into the terminal cisternae via active transport with the hydrolysis of one ATP. Each crossbridge cycle is associated with the hydrolysis of one ATP molecule, and the events are repeated as long as the muscle is stimulated and the intra-cellular environment is favourable.

Figure 3: Sequence of Events and Potential Fatigue Sites

(Adapted from Edwards, 1983)



2.3 FORCE PRODUCTION

While this theory represents the fundamental site and activity of force production, one must consider the chain of events leading to the stimulation of the motor unit. Each of these, along with the activity within the sarcomere, may be influenced by a number of factors. Figure 3, page 16, illustrates the sequence of events leading to the development of tension and the sites where force generation may be influenced.

2.3.1 Central

The central factors refer to events occurring prior to the neuromuscular junction (Edwards, 1983). These include the degree of motivation, the degree of 'psyching up', and the degree of neuromuscular inhibition. The degree of motivation may be influenced by such factors as experience and pain tolerance (MacDougall, 1975). The degree of neuromuscular inhibition, as cited by O'Bryant (1985a) and Cioazzo et al. (1981), is said to be a protective mechanism mediated through afferent impulses on the reticular formation. It is reported to be altered by training and perhaps by specific techniques (Cioazzo et al., 1981). O'Bryant (1985a) stated that the degree of inhibition is likely related to skill acquisition.

The recruitment of different fibre types will have a profound effect on development and pattern of force production. The 'size principle', as proposed by Henneman et al. (1965), describes the orderly recruitment of motor units in a specific sequence according to the motorneuron size and type of unit, to produce some combination of force and velocity of

contraction as a result. Accordingly, the small motorneurons would be the first recruited and thus the slow twitch (ST) muscle fibres, which are less able to produce high tension levels than fast twitch (FT) would be first activated (Thortenssen, 1976). However, a maximal exercise requiring high force output necessitates the recruitment of fibres which are able to provide the necessary force-i.e. the FT fibres. There is considerable controversy as to the flexibility of recruitment order in different exercise conditions. According to Grimby and Hannerz (1977), studying voluntary contractions of the toe extensor muscles, the order of recruitment may vary according to different movement speeds, to the intensity required and to the degree of cortical stimulation. According to Thortensen (1976), the central nervous system appears to be able to adjust the sequence of motor unit recruitment to selectively involve large units when very forceful and/or rapid movements are required.

In a roundtable discussion on determining factors of strength (involving the following physiologists, - Edgerton,V.R., MacDougall, D., O'Bryant H., Sale, D., Tesch, P.,), three main factors were cited; the number of motor units firing; the frequency of motor units firing; and the degree of synchronization of firing. A positive correlation with each of these factors to force generation has been reported, although there is some debate over the effect of synchrony at certain speeds (Miller 1981, as cited by Sale, 1985).

Another central mechanism reported to influence force production in voluntary movement is proposed by Denny-Brown (1966). The term 'psyching up' may refer to an excitory biasing mechanism whereby afferent nerve

impulses combine at interneuronal cells to form "purposive patterns for exciting or inhibiting interneurons". By countering a tonic inhibitory bias, synapses from interneurons may keep a membrane potential close to its threshold firing levels, so that a small additional depolarization is all that is needed to make it spill over into discharging. This is particularly important for the large motorneurons (innervating the FT fibres) which require a high degree of depolarization for activation to occur:

2.3.2 Peripheral

Of the peripheral factors, the most commonly cited are;

1) the quantity of muscle mass involved (including both the diametre and length of the muscle),

2) the quality of the muscle mass (fibre type),

3) the geometric properties of the muscle (internal configuration and attachment sites).

Muscle volume is credited with determining a large degree of the ability to develop tension. High correlations between volume and tension have been reported historically (Astrand and Rodahl, 1977; Komi, 1979) although the degree of correlation is dependent on the method used to measure volume. The reported differences in strength with respect to age and gender (Astrand and Rodahl, 1977) may be largely attributed to the differences in muscle volume.

The effect of muscle fibre type on tension development has been studied extensively, and several researchers (Ivy et.al., 1980; Thortenssen, 1976) have reported that muscles with a high percentage of FT fibres can generate higher tensions, particularly during dynamic contractions that surpass a certain critical velocity (Bohannon, 1983). Studies showing this relationship include isometric (Jones, 1983; Tesch and Karlsson, 1979), isotonic (Grimby and Hannerz, 1977), and isokinetic (Ivy et.al., 1980) contractions. Most of these compare force or torque values with the percentage of FT fibres as determined by muscle biopsy. Studies looking at selective glycogen depletion have indicated that when the force exerted is greater than 20% of maximum voluntary contraction, tension depends primarily upon FT fibres (Gollnick et.al., 1974).

The internal configuration refers to the shape, fusiform or pennate, of the muscle. Pennate fibres are said to produce more tension, but with a limited range of motion (Komi, 1979). The points of origin and insertion may also affect tension development, but a more detailed description is beyond the scope of this paper.

The exercise conditions will partly determine the degree of tension produced. Isometric, isotonic and isokinetic contraction vary in the manner of contraction and in the amount of force that can be produced under each condition (Komi, 1979). The differences in tension development capacity under concentric and eccentric contraction conditions have been well documented (Kaneko et.al., 1983; Komi, 1983; Seliger et.al., 1980).

When Kaneko and coworkers (1983) studied concentric and eccentric contractions at different contraction velocities, they found that eccentric contractions resulted in performance of high mechanical work with low energy expenditure, and that at all velocities the work values for eccentric contractions were higher and the energy output values were lower. The force capacity of eccentric contraction has been observed to increase at higher velocities, according to force velocity curves (Asmussen et.al., 1965; Komi, 1983), while the energy expenditure is reportedly much lower (Seliger et.al., 1981) relative to concentric contraction.

The final factor to be discussed is the storage of energy in the elastic components of muscle. This is considered to be a normal muscular function during the preparation phase of ballistic movements (Komi, 1981; O'Bryant, 1985b). The storage occurs during a 'critically timed' muscle stretch followed immediately by a muscle contraction to produce greater force. This is due to elastic recoil and the stretch reflex (a central nervous system response stimulating a forceful contraction of stretched muscle fibres). As described by O'Bryant (1985b), a 3% lengthening of the series elastic component at the Z disc causes the energy thus stored to be released during propulsive phases of movement. This, along with the stretch reflex, potentiates the force developed (Cavanaugh, 1978 in Komi, 1983). Any single, or any combination of the factors proposed here may influence the force of contraction (peak force). The next two sections shall address the production of force over time, specifically referring to a short-term, dynamic, high intensity test.

2.4 ANAEROBIC LACTIC ENERGY TRANSDUCTION

It is well accepted (Astrand and Rodahl, 1977; Bouchard et.al., 1982; Gollnick and Hermanssen, 1974; Hermanssen, 1982; Sale, 1983) that during short term exhaustive exercise the energy needed is derived mostly from anaerobic sources. Under these conditions the degradation of glycogen to lactate represents a major source of energy for the muscle. The anaerobic system associated with exercise durations of 30 seconds to two minutes is known as the anaerobic lactic system. According to Medbo et.al., 1988, who studied anaerobic capacity in terms of the oxygen deficit measure, it is only in events of close to two minutes that the full anaerobic capacity can be utilized.

The initial anaerobic event at the onset of exercise is the splitting of ATP during muscular contraction, with the ATP being replenished by the transfer of a phosphate from creatine phosphate (CP) to ADP. This source is exhausted within 10-20 seconds. The breakdown of glycogen to lactate (glycogenolysis), which, contrary to previous belief (Astrand and Rodahl, 1977; Katch and Weltman; 1979; Margaria, 1968), may begin within five seconds of the onset of exercise (Jacobs 1986; Saltin, 1986), also provides energy to the contracting muscle. For durations of longer than 30 seconds of supramaximal effort, this source is significantly more important quantitatively than the phosphagen stores (Gollnick and Hermanssen, 1974). Glycolytic breakdown of one mole of glucose or glycogen to lactate results in the net gain of two or three moles of ATP respectively. This represents a significant amount of energy, and the rate at which this occurs allows the muscle to perform at a much higher intensity than would energy from oxidative sources.

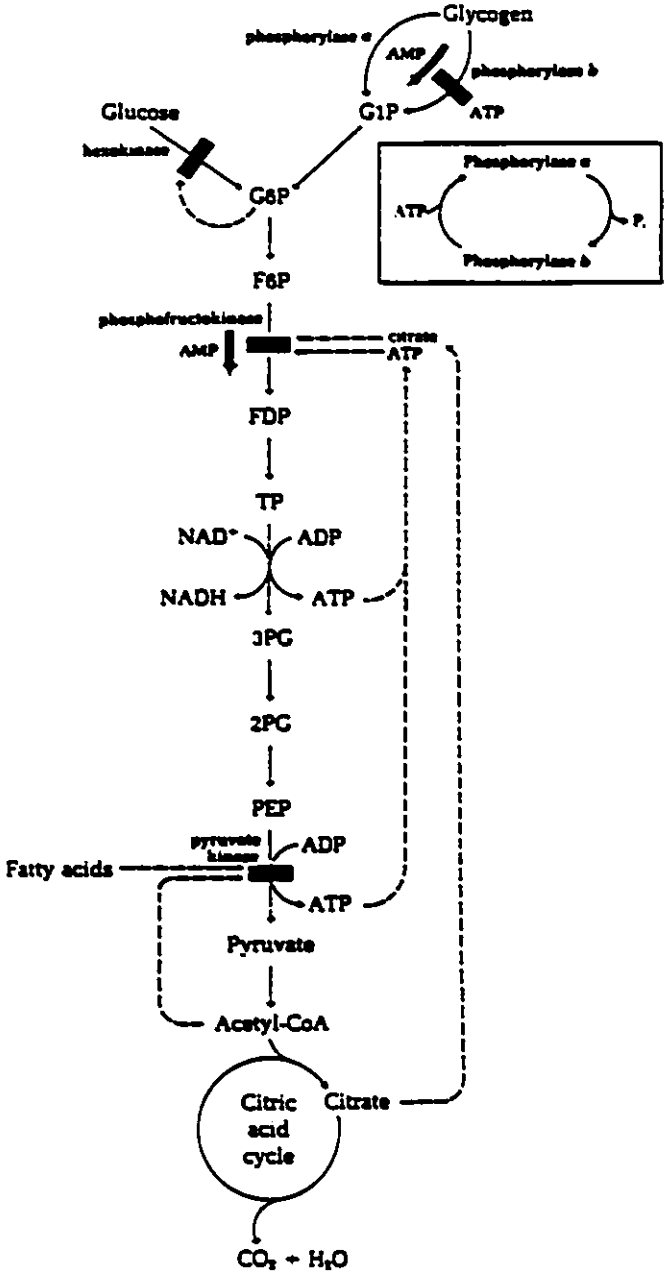
2.4.1

Regulation of Glycolysis

According to Lehninger (1982), the process of glycolysis is essentially irreversible, proceeding with a large net decrease in free energy and thus the equilibrium is very much in favour of lactate formation. The accumulation of lactate in the muscle and blood is said to represent an indication of the extent of anaerobic glycolysis (Astrand and Rodahl, 1977; Hultman et.al., 1982). In support of this are the high levels of lactate that have been reported by numerous researchers (Hermanssen, 1969; Medbo and Sejersted, 1985; Thomson, 1981; Thomson and Garvie, 1982) at the end of high intensity exercise. These values may be dissimilar for athletes in different sports as a result of varying capacities for lactate production and clearance which would result from different modes of training.

There are two major steps in the breakdown. The first is the phosphorylation and subsequent cleavage of glucose to form glyceraldehyde-3-phosphate (G-3-P), involving the utilization of 2 moles of ATP. The second step is the transformation of G-3-P to lactate, involving oxidoreduction steps whereby ADP is rephosphorylated, and the net energy gain is 3 ATP molecules for each molecule of glycogen. A summary of the individual steps is presented on page 24.

Figure 4: The Glycolytic Pathway (from Lenhinger, 1985)



While the process of glycolysis is regulated by the actions of 11 enzymes, it is assumed that the control of glycolysis is regulated by two key enzymes; glycogen phosphorylase (GP), and phosphofructokinase (PFK) (Astrand and Rodahl, 1977; Edwards, 1983; Gollnick and Hermanssen, 1974; Hultman and Sahlin, 1980; Lehninger, 1982; Sahlin, 1978). GP catalyzes the phosphorylation of glycogen into glucose-1-phosphate. This enzyme exists in a form which is inactive (phosphorylase b) except in the presence of 5-AMP, and a form which is active (phosphorylase a) in the absence of 5-AMP. Activation of this enzyme may occur as a result of mediation by a series of reactions (Figure 5, page 26), involving the action of adrenergic hormones, and a response of phosphorylase b kinase to elevations in Ca++ concentration.

The Ca++ concentrations inducing this transformation are of the magnitude released from the SR during muscular contraction (Drummond et.al., 1969; and Brostromm et.al., 1971). The other method of activation involves the stimulation of the adenyl cyclase system by adrenergic hormones, resulting in an increased level of 5-AMP, and conversion of the inactive b form to the active b form. Transformation of this enzyme during muscular contraction from the b to the a form in human studies has not yet been confirmed (Gollnick and Hermanssen, 1974). Chasiotis et.al., (1982) found that during maximal bicycle exercise leading to exhaustion within 4-6 minutes, the phosphorylase a activity initially increased 1.6 fold, and the synthase level correspondingly dropped to about one half of the resting value, correlating with the enhanced rate of glycolysis during exercise.

Figure 5: Activation of Glycogen Phosphorylase
(from Gollnick and Hermansen, 1973)

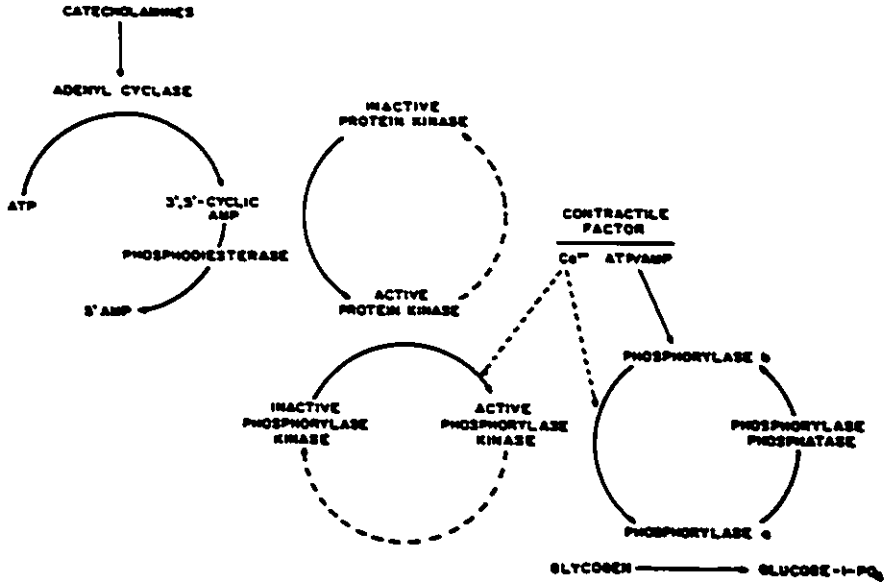


Fig. 1. Diagram for the activation of glycogenolysis via the enzyme phosphorylase. A hormonal control by the catecholamines and a contraction-coupled control via Ca^{2+} is shown.

Since the concentration of inorganic phosphate (Pi) changed from resting levels to 20-30 mM/l, which is within the Km values for both phosphoylase a and (a+b) the authors concluded that Pi is a factor determining phosphorylase activity, and that the reaction provides a link between CP breakdown and glycogen utilization in muscle.

Care must be taken in interpreting results involving changes in substances during exercise, since there is evidence to suggest that the water content in muscle also changes (up to 11%). According to Hermanssen (1982), this may introduce a dilution factor intracellularly. Conversely, there may be a concentration factor extracellularly.

The glucose-1-phosphate formed from the phosphorylase reaction may then be converted to yield glucose-6-phosphate (G-6-P). G-6-P is isomerized to form fructose-6-phosphate (F-6-P). Alternatively, D-glucose may be phosphorylated by ATP via the hexokinase reaction to yield G-6-P. The next step is catalyzed by the second major regulatory enzyme, phosphofructokinase (PFK). PFK is present in the lowest concentration of any of the enzymes, thus making it the rate-limiting enzyme. It is an allosteric enzyme, showing a complex dependence of its reaction velocity on the concentration of its substrates. Its activity is inhibited by high concentrations of ATP, CP, H+ ions, fructose-1,6-diphosphate and citrate (Astrand and Rodahl, 1977; Gollnick and Hermanssen, 1974; Lehninger, 1982), but may be stimulated by high concentrations of ADP, AMP, and inorganic phosphate (Pi). The decline in ATP with the concurrent rise in the other adenyl nucleotides during exercise may exert a key role in the regulation of PFK activity. The production of high lactate levels re-

sulting in a decrease of muscle and blood pH can also serve to inhibit the reaction velocity of PFK (Wenger and Reed, 1976). Fructose-1,6-diphosphate, the product of this reaction, is then converted to glyceraldehyde-3-phosphate.

In the second stage, glyceraldehyde-3-phosphate is oxidized by NAD+ via the action of glyceraldehyde phosphate dehydrogenase, with the uptake of Pi. This forms phosphoglycerolphosphate, which then donates its acyl phosphate group to ADP to form 2 ATP and 3-phosphoglycerate. After dehydration to enolase, the phosphoenolpyruvate formed donates its phosphate group to ADP. The product of this reaction, pyruvate, is reduced to lactate and NAD+, since the required rate of ATP production is too rapid to permit the preferred oxidative regeneration of ATP (Lehninger, 1982).

This final reaction is catalyzed by the enzyme lactate dehydrogenase (LDH), which exists as five isoforms, differing in their dependence on substrate concentration. Each isoform is composed of two subunits which are combined in a tetramere; H (heart specific) and M (muscle specific). LDH isozymes with primarily H subunits (H-LDH) favour the oxidation of lactate to pyruvate and are located in more highly oxidative tissues (cardiac and ST muscle fibres) and may also be found in the mitochondria (Sjodin, 1976). The M-LDH forms favour the reduction of pyruvate to lactate, are associated with glycolytic function and are predominant in the sarcoplasm of the FT fibres, although Sjodin (1976), from autopsy studies, has suggested that this form may be membrane-bound to the SR. This has been confirmed by Tesch (1980), studying human muscle biopsies after

maximal exercise of 30 and 60 second durations, who found that the total LDH and the M-LDH activities were positively correlated to lactate concentrations, to muscle fatigue, and to fibre type distribution. In an eight week training study using healthy males, Sjodin (1976), found that the activity of LDH could be altered by endurance training resulting in a decreased total LDH activity and an increased H-LDH activity, suggesting a mechanism for increased oxidation of and thus delayed accumulation of lactate. This indicates a mechanism whereby endurance training may enhance the removal of lactate by oxidation to pyruvate. No change, however, was seen in the activity of these isoforms after eight weeks of anaerobic training, although an increase in peak post-exercise lactates and in performance was observed. Whether the intensity of anaerobic training was insufficient to stimulate a response in the enzyme activities remains to be seen.

The formation of lactate in man is usually regarded as a result of the need to reoxidize extramitochondrial NADH by pyruvate reduction to lactate (Karlsson 1979). The oxidative function in the dehydration of glyceraldehyde-3-phosphate is dependent upon the conversion of NAD+ to NADH. This requires a means of regenerating NAD+. In the absence of oxygen, this may be accomplished by the LDH reaction which results in the electrons from NADH being transferred to pyruvate, re-oxidizing the NAD+ and converting the pyruvate to lactate. However, more recent research has indicated that the malate-aspartate (M-A) shuttle may also play a significant role in the reoxidation of NADH under exercise conditions (Schantz, 1986). His studies indicated a significant increase in these

shuttle enzymes as a result of endurance training, as well as an approximately 48% higher level of these enzymes in endurance trained runners when compared with untrained subjects. While the shuttle mechanism would not normally play a role in anaerobic glycolysis, a number of studies have indicated (Cerretelli et.al., 1979; Pendergast et.al., 1979; Vandewalle et.al., 1987 that endurance trained subjects have a more rapid oxygen transient than do untrained subjects, and thus the M-A shuttle may play a role in the latter part of the exercise. Wasserman et.al., (1985) proposed that the increase in glycolysis is so rapid that the mitochondria cannot utilize pyruvate rapidly enough to prevent its elevation in the cytosol, resulting in an increase in lactate by mass action. This theory is contradicted by Karlsson's (1971) results which suggested that the relative increase in pyruvate is not sufficient to cause a mass action effect. However, this would not invalidate the conclusion that the relative concentrations of pyruvate and lactate may reflect the balance between the rate of mitochondrial clearance of pyruvate and of glycolysis, and that this ratio (pyruvate : lactate) might be expected to decrease when the cell redox state is reduced. The rate of formation of lactate will depend primary on the activity of the LDH (Karlsson, 1979; Sjodin, 1976; Tesch 1978; Tesch, 1980; Wenger and Reed, 1976) since the pyruvate and NADH formed will be substantial during intense exercise.

2.5 MUSCULAR FATIGUE AND SUPRAMAXIMAL EXERCISE

For individual muscle cells, there is an intimate relationship between excitation-contraction processes and energy metabolism. Failure of one will affect the second and subsequently cause muscular fatigue. Any factors which impair either or both of the contractile or metabolic machinery will result in fatigue and will ultimately limit performance. As mentioned earlier, muscular performance associated with two minutes of high intensity exercise is highly dependent upon the glycolytic energy transduction capability of the muscle. The inability of the anaerobic system to replenish the ATP stores at a rate demanded by the performance characteristics will result in depletion of the ATP stores, and thus a decline in force generating capacity. Lactate, the usual end product of this energy system (glycolysis) has long been recognized as a major contributor to fatigue (Asmussen, 1974; Gollnick and Hermanssen, 1974; Hultman and Sahlin, 1980; Karlsson, 1979; Tesch, 1980).

According to Sahlin (1983), lactate content in muscle can increase about 30-fold during intense exercise to fatigue, contributing to high correlations found between lactate levels and fatigue. As mentioned previously, the presence of high levels of lactate have been found in both muscle and blood after short intense exercise. Recent research has indicated however, that the mechanism may be indirect, caused by the decline in pH as a result of the H+ ions donated as lactic acid dissociates to lactate ion and H+. There is also evidence that the concurrent accumulation of Pi in it's diprotonated form, along with the decline in pH, may directly affect the contractile mechanism (Nosek et.al., 1987).

While a close correlation between muscle lactate concentration and fatigue was demonstrated by Fitts and Holloszy (1976), a discrepancy between these quantities during recovery indicated that another associated factor was responsible (Tesch 1978). Sahlin (1983) calculated that 85% of the H+ ions liberated during intense exercise could be attributed to lactate production. pH levels on the order of 6.4-6.6 were found concurrent with lactate levels of 25-30mM/kg wet weight in muscle. This was confirmed by Karlsson (1971) and Hermanssen (1969). Donaldson (1983) found that a decline in force generation was linearly related to an increase in intracellular H+ and ADP during direct stimulation of skinned frog muscle.

While the concentration of lactate in blood only represents an instant in the dynamics of lactate production, release and clearance, several authors have indicated that post-exercise blood lactate may be used as an indicator of intensity and of the extent of energy production via glycolysis occurring during exercise (Astrand, 1984; Cheetham,1986; Gollnick and Hermanssen, 1974; Gollnick, 1983).

The effect of lowered pH can cause a change in enzyme activity by;

a) changing the charge of ionizable groups and thus the affinity of the enzyme for substrates or products,

b) altering the conformation and thus the catalytic activity, changing the ionic state of the intermediates or involved inhibitors/activators and thus indirectly influence the reaction (Hultman and Sahlin, 1980).

Lowered pH is reported to inhibit the activities of the two key enzymes of glycolysis; GP and PFK (Edwards, 1983; Gollnick and Hermanssen, 1974; Tesch, 1980; Wenger and Reed, 1976).

The activity of GP is indirectly influenced by an effect of H+ ion on phosphorylase b kinase. This enzyme has been shown to be inhibited at low pH, both in vitro (Krebs et.al., 1964 as cited in Gollnick and Hermanssen, 1974) and in vivo (Danforth, 1965). An effect on the activity of adenyl cyclase has been reported (Mawatari et.al., 1974), which results in a decreased cAMP formation and decreased activity of phosphorylase b.

The activity of PFK is extremely sensitive to pH changes and is reported to be almost completely inhibited at pH 6.4 (Danforth, 1965). A pH of 6.4 has been seen at the end of exhaustive exercise (Sahlin 1978). With the nuclear magnetic resonance technique, a pH of below 6.0 has been reported in human skeletal muscle at exhaustion, suggesting that previous values may have been overestimated (Sjogaard et.al., 1985 in Sahlin, 1986). Hultman and Sahlin (1980) have proposed a pH-dependent effect on equilibrium reactions involving the NAD+/NADH ratio, and on the ionic complexes of ATP and ADP.

Changes in pH may have significant effects on a number of steps in the excitation-contraction sequence. Bianchi (1982) and Hultman et.al., (1982) have reported an alteration in Ca++ concentration in the T-tubule system as a result of lowered pH. This raises the threshold for coupling of the action potential to contraction, lowers the number of crossbridges formed, and thus decreases the force which the muscle is capable of

producing. Increased binding capacity of isolated SR membranes for Ca++ ions when pH values are less than 6.6 has been reported by Nakamura and Schwartz (1972) and Fabiato and Fabiato (1978). This results in a decreased amount of Ca++ released by the SR, and thus less ion available for contraction. It has been proposed that the H+ ions may compete with Ca++ ions for binding sites on the troponin (Edwards, 1983; Nakamura and Schwartz, 1972; Robertson and Kerrick, 1976; Wenger and Reed, 1976). This would result in a decrease in the number of crossbridges formed and ultimately in decreased force production. This competition theory has been challenged by several authors (Donaldson, 1983; Hermanssen, 1982; Fabiato and Fabiato, 1978; Karlsson, 1979).

A depression of Ca++ sensitivity of the force generating apparatus has been observed in animal studies (Donaldson and Hermanssen, 1978; Robertson and Kerrick, 1976). It is proposed that there would be an increased threshold for the amount of Ca++ required for contraction to reach a given tension (Fitts et.al., 1978; Hultman et.al., 1982; Tesch, 1980). Also, an alteration in the Ca++ resequestering ability of the SR (Belcastro et.al., 1981) was seen in exercised rats after exhaustion. This interpretation was based on a 21% decrease in the Ca++ accumulation ability of the SR ATP-ase Ca++ pump. Hultman and coworkers (1982) concluded that the disruption of the Ca++ translocation process may be responsible for the reported decline in force production. Finally, Dawson et.al., (1978), and McCartney (1983), have suggested that the acidosis may alter the amount of energy available for work per molecule of ATP hydrolyzed, and subsequently alter cross-bridge formation.

A recent study by Nosek et.al., 1987, on isolated rabbit psoas muscle, suggests that a decrease in intra-cellular pH associated with fatigue may further depress force by transforming more of the total inorganic phosphate within the cell to the inhibitory diprotonated form. This reported conversion is supported by the work of Gollnick (1982), who found that a drop in pH from 7.0 to 6.5 transfers 50% of the available substrate HPO2 to H2PO4. This form may interfere with cross bridge formation by preventing the release of Pi from the attached cross bridges. Wilson et..al., confirmed the occurrance in human studies when they found a strong relationship between fatigue during maximal elbow flexion, and diprotonated Pi.

To summarize, the reduction in force production may be accounted for by any of;

a) a reduction in the maximal rate of ATP resynthesis as a result of the H+ ion effects on glycolytic enzyme activity,

b) a direct effect of H+ ion concentration on the force generating apparatus, (possibly in combination with diprotonated Pi ion),

c) a reduction in the energy released from ATP hydrolysis,

d) an alteration in Ca++ translocation and activation.

Fatigue may ultimately be due to failure in the rate of the energy supply to meet demand, but the precise expression of this deficit may vary according to whether failure of activation may predominate over failure of energy supply.

A number of other factors have been proposed as influencing muscular fatigue.

The majority of early fatigue research was conducted to determine whether fatigue is central or peripheral in origin. Central fatigue is defined as the impairment of efferent signals originating proximal to the motor neurons. In 1967, Ikai et.al., as cited in Asmussen, 1979, analyzed repeated maximal isometric contractions to fatigue in the adductor pollicus muscle. The muscle was then stimulated electrically, and a strong increase in force occurred, implicating central fatigue. Similar studies (Grimby and Hannerz, 1977; Bigland-Ritchie et.al., 1978) have confirmed these results. Asmussen concluded from the results of these studies that central fatigue is caused by certain nerve afferents from fatigued muscles that stimulate the inhibitory part of the reticular formation and cause a decrement in the number or intensity of efferent signals to the muscles.

Although psychological factors have also been implicated, as mentioned in section II, Merton (1954) found evidence whereby electrical stimulation did not produce any increase in force after exhaustion. Merton stated that central fatigue is not likely to be a limiting factor for trained athletes, and other researchers have suggested a significant variation both within subjects and between subjects (Edwards, 1983).

Associated factors have also been implicated, such as the level of motivation, experience, and pain tolerance. Bigland-Ritchie and coworkers (1978) found that up to 30% of muscular fatigue could be accounted for by central factors. Their results indicated that fatigue may be caused distal to the central nervous system, either at the neuromuscular junction or within the contractile elements.

Stephens and Taylor (1972) presented data on humans that they interpreted as giving evidence that neuromuscular junction fatigue is most important during the first minute of maintained voluntary muscle contraction and that contractile element fatigue predominates beyond that point. Failure of the transmission mecnanism is thought to occur as a result of depletion of acetylcholine stores, or by the loss of excitability of the post-synaptic membrane.

During exercise, the recruitment of different fibre populations is seen to change as evidenced by a shift in the power spectrum of EMG recordings from high frequency to low frequency spectrum (Edgerton, et.al., 1983; Edwards, 1982; Komi, 1981). This is believed to be the result of shifting motor recruitment as FT fibres are unable to maintain the expected force and so more ST motoneurons are recruited in an attempt to compensate. The extent of muscle fatigue varies to a considerable degree according to the characteristics of the muscle fibre, and to the proportion of muscle fibre types in the muscle groups used in the exercise. Research has been focused on the the behaviour of different muscle fibre types in terms of fatigueability. In fact, this property of fatigue has been included in the fibre type nomenclature.

Table 1.

Metabolic and Functional Charactaristics of FT and ST Fibres

(adapted from Astrand and Rodahl, 1977; Karlsson, 1979)

Properties	FT	ST
Glycolytic enzyme activity		
- PFK	high	low
- GP	high	low
- LDH (total)	high	low
- H-LDH	low	high
Mitochondrial enzyme activity	low	high
Activity of enzymes involved in contraction	high	low
Phosphagen stores		
-ATP	low?	high?
- CP	high?	low?
- glycogen content	high?	low?
Capillary density	low	high
Myoglobin content	low	high

Table 1: continued

Properties	FT	ST
Fatiguability with short-term intense activity	high	low
Fatiguability with prolonged activity	high	low
Training effect		
-strength and sprints	↑	↓
- anaerobic	↑	↓
- aerobic	↓	↑

Muscles are divided into two categories according to the metabolic and fatigue properties. See table 1 (page 39) for details.

Fast twitch fibres, as a consequence of the high glycolytic capabilities and myosin ATP-ase activities, are associated with a high rate of fatigue. This is confirmed by numerous studies involving some form of force fatigue testing (isometric, isotonic, or isokinetic loading) and/or muscle biopsy sampling (for percentage of fibre type, glycogen depletion patterns and/or relative lactate production) in order to determine the association between fatigue and fibre type. Numerous studies have shown a consistent positive correlation between force values (peak and decline) and the percentage of FT fibre (Edgerton et.al., 1983; Edwards, 1983; Hermanssen, 1969; Gollnick, 1968; Karlsson, 1979; Komi, 1979; Tesch, 1980; Thortenssen 1976; Viitisalo and Komi, 1978). However, none of these studies examined any distinctions between possible subgroups of FT fibres. In a study mentioned previously by Tesch et.al., (1978), using biopsies from human vastus lateralis after 30 and 60 seconds of maximal dynamic exercise, differences between the fibre types in terms of each of muscle lactate, total LDH and M-LDH activity were found, and these were positively correlated to fatigue. It was concluded that lactate or associated pH changes primarily in the FT fibres was largely responsible for impaired muscle function. There is some suggestion (Hermanssen, 1982) that the different fibre types may respond differently to changes in pH.

Studies of glycogen depletion measured by muscle biopsy after supramaximal effort show a trend toward selective depletion in the FT fibres

(Edgerton, 1976). One explanation for the different conclusions as to the nature of fatigue may stem from the different forms of contractions used in the studies. Many studies used prolonged isometric contractions, which is primarily an artificial laboratory situation and has little application in the sport performance field. Isometric contractions tend to partially or totally occlude blood flow through the active muscle, which results in a lack of oxygen and a build up of lactate and heat in the muscles, thus causing fatigue at an early stage (Astrand, 1984). Neither the isometric nor isotonic tests have been sufficiently standardized, and therefore make comparisons difficult. According to Karlsson (1979), control of the rate of contraction is necessary to obtain reliable force output values. The development of isokinetic dynamometres has allowed for greater control of measured force output. Also, the more recent development of nuclear magnetic resonance (NMR) and skinned fibre techniques have allowed for greater control and accuracy in the study of fatigue.

Many of the factors associated with fatigue are dependent upon the type of activity and motor unit used. Variations between fatigue curves at different velocities could reflect differences in fatigueability of selectively recruited motor units. Variations in force production have also been reported with respect to concentric and eccentric contractions. According to Kaneko et.al., (1983), the mechanical behaviour of muscle during eccentric contractions results in performance of high mechanical output with lower energy expenditure. There are reports of up to three-fold greater force values in eccentric contractions (Seliger et.al., 1980). Komi and Rusko (1974) observed that after 40 contractions

of forearm flexor muscles, the eccentric forces recorded represented 50% of maximal values , whereas the values for concentric force represented 80% of maximal force. It was then suggested that neural input and energy requirement are equal in maximal effort, but that the differences in fatigue emphasized the extreme loading of the elastic component of muscle during high tension eccentric contractions. While the exact mechanisms by which the high level of muscular tension is attained in eccentric work is still unknown, it is believed that output from the elastic components is enhanced during the resistance to stretch.

While it is likely that some combination of the factors described in this section contribute to muscular fatigue in supramaximal exercise, the production of energy via the anaerobic lactic system is commonly perceived as the major contributing determinant, and it is to a certain degree measurable by post-exercise lactate values.

2.6 MUSCULAR FATIGUE AND ATHLETIC PERFORMANCE

Greater understanding of the origin of muscular fatigue and of the limits of anaerobic capacity in athletic performance can lead to improved methods of training and performance by athletes. The key to athletic performance (technique and genetic factors being equal) lies largely in the ability to delay fatigue while maintaining a required maximal intensity. A better understanding of the factors responsible for fatigue and thus reduced performance will aid in the development of training procedures to produce physiological changes that will aid in the delay of fatigue.

An intense exercise may be performed partly aerobically and partly anaerobically, with a greater or lesser reduction in force production varying with the relative severity of work. A well tolerated exercise in steady state, as in a cross country ski race, becomes anaerobic when the athlete begins to sprint at the end of a competition. The bulk of the literature, however, deals with anaerobic lactic capacity and peak forces in terms of those athletic performances which involve a single bout of effort lasting between 30 seconds and 2 minutes, such as a 400 metre run, or 100 metre swim (Kindermann and Keul, 1977).

Many of the tests used rely on some power, or total work value as a predictive measure of the anaerobic system, most often using a bicycle ergometer and measuring the work output during exercise of 30 seconds to two minutes, i.e. Wingate, Katch, Cunningham (MacDougall et.al., 1983). Many of these used no lactate measures. Simoneau (1983), using a 90 second test found that lactate values after testing were often below those maximal values found in the literature. Possible explanations for variations may be attributed to differences in protocol, such as time of lactate sampling, test duration, use of different muscle groups, and different subject populations with varying fitness levels.

A number of researchers have measured lactate under anaerobic lactic test conditions. Tesch (1980) found very high lactate levels after 60-120 seconds of maximal cycling - 25.8 mM/kg muscle in FT fibers and 16.7 mM/kg wet weight in ST fibers. He also found levels of lactate after approximately 60 seconds of downhill skiing to be on average 17.8 mM/kg wet weight but with no difference between the fibre types. This

may be related to the differences between the basically isometric contractions of skiing as compared to the dynamic contractions in cycling.

Hermanssen (1969), found that of 13 running tests of various durations, the average blood lactate values at exhaustion were approximately 18mM/l. This occurred at the same time as subjective fatigue on the part of the subject. Komi et.al., (1977) measured the blood lactate of athletes from various sports after both maximal leg and arm tests. They reported a range of peak lactate values from 9.0 to 13.9 mM/l, and on comparison with muscle biopsies, also found a positive correlation of blood lactate with percentage of FT fibre. Kindermann and Keul (1977) tested the blood lactates of elite athletes from various sports during the first 10 minutes after international competitive events. Those sport events representing maximal dynamic efforts of 1 - 1 1/2 minutes (eg. 500 m run, 100m swim, 1 000m speed skate) elicited the highest values, ranging from 15 to 22 mM/l. Intra-individual comparisons of swimming exercises using different muscle groups found that lower pH and higher lactate values occurred in leg work compared to arm work. Astrand and Saltin, (1961) in Saltin (1986), found that when arm work was added to leg work, the anaerobic capacity, as measured by oxygen deficit, increased by approximately 50%. They concluded from this that anaerobic capacity is a function of muscle mass.

Hermanssen (1969), proposed that the limiting factors for energy production and utilization for anaerobic work include:

1) the ability to tolerate a high level of lactic acid and low level of pH.

2) the degree of training, which may result in a decreased production of lactic acid for a given power output, and a higher degree of tolerance for high levels of lactate in blood and muscle (Karlsson and Saltin, 1970).

3) The efficiency of the cardiorespiratory system; the longer the supramaximal bout, the more critical this becomes.

Those events associated with a high degree of aerobic endurance work elicited lower relative values ranging from 2.5 to 13.8 mM/L (Kindermann and Keul, 1977; Komi et.al., 1979). These lower values may be interpreted as a product of factors involved in the effect of endurance training on the rate of lactate production and clearance from the muscle and/or blood. Table 2, page 47, summarizes some of the major responses which may influence lactate production and clearance.

The ultimate result of these factors, in combining to limit lactate production and enhance clearance, is to decrease the amount of lactate accumulated and thus the degree of interference with muscle function. Although these factors help to explain in part the lower blood lactate values found in endurance athletes, it may also be true that energy transduction via glycolysis may be decreased with training, although there is little evidence of a decrease in glycolytic enzyme activity with endurance training (Schantz, 1986) with the exception of hexokinase activity.

Table 2: Endurance Training Responses and Lactate Turnover

Endurance Training Response	Effect on lactate turnover
1. ↑ in H-LDH, ↓ in total LDH	↓ production
2. ↑ capillarization	↑ clearance
3. ↑ mitochondrial density	↑ clearance
4. ↑ oxidative enzyme activity	↑ clearance
5. ↑ malate/aspartate shuttle enzyme activity	↑ clearance
6. ↓ gluconeogenesis during exercise	↓ production
7. ↑ rate of increase of VO2 in transition from rest to exercise	↓ production
8. slower utilization of muscle glycogen and blood glucose	↓ production
9. ↓ lactate production at a given exercise intensity	↓ production
10. ↑ ability to oxidize free fatty acids	↓ production
11. tendency for endurance athletes to have higher ST percentages	↓ production and ↑ clearance
12. ↑ utilization of lactate by ST fibres	↑ clearance
13. ↑ buffering capacity of blood?	↑ clearance

Table 2: continued

Sources
1. Sjodin, 1976; Holloszy and Coyle, 1984
2. Tesch and Wright, 1983;Saltin, 1986
3. Holloszy and Coyle,1984; Tesch and Wright, 1983
4. " " " "
5. Holloszy and Coyle,1984: Schantz, 1986
6. Donovan and Brooks, 1983
7. Pendergast et al., 1979
8. Holloszy and Coyle, 1984
9. Donovan and Brooks, 1984
10. " " " ; Holloszy and Coyle, 1984
11. Astrand and Rodahl, 1977; Tesch et al, 1979
12. Klausen et al., 1982
13. Saltin, 1986

Bouchard et.al., (1982) state that laboratory tests for anaerobic capacity are of greatest relevance to the athlete when they simulate the actual mode of exercise and involve the specific muscle groups that are trained. This indicates a need for specialized ergometry equipment.

2.7 MUSCLE FATIGUE AND ANAEROBIC CAPACITY IN CROSS COUNTRY SKIING

While Bergh (1980) states that 90% of energy production comes from aerobic processes, cross country ski racing involves subtlely varying levels of intensity and workload that shift intricately between aerobic and anaerobic systems. A skier must be able to maintain performance at a high level during changes in terrain and so must be able to both supply energy aerobically and to develop tolerance for the anaerobic work performed. For skiing, which requires the use of a large muscle mass, one might expect the potential for anaerobic capacity to be larger than for other endurance athletes who use less muscle mass. Also to be considered is the finishing sprint at the end of the race which alters the nature of the exercise performed from largely aerobic to anaerobic (de Bruyn - Prevost, 1978).

While the topics of aerobic power and anaerobic threshold in cross country skiing have been extensively investigated, there appears to be very little research reported in the literature regarding the anaerobic lactic system of cross country skiers. Peak force values of a single explosive nature have been measured (Ekstrom, 1981; Haymes and Dickinson, 1980), but this author has been unable to find any report associated with the lactic system. According to Bergh (1980), no attempts have

been made to measure oxygen debt after activity. However, blood lactate levels have been measured following competitions of various lengths (see table 3, page 50). Blood lactate levels are seen to vary, though the lactic acid levels after the shortest races, 5 and 10 kms, are quite high and indicate a high anaerobic contribution during portions of these races. This may apply particularly in relay races, where the 'tempo' is even more uneven due to tactical strategies. Because the samples are taken at the end of races, it may be assumed that they represent the anaerobic contribution of the latter part of the race.

When the separation between times for the top finishers is often no more than a few seconds and as little as one tenth of a second, a two second time difference in a 15 minute race corresponds to 0.2% in time, and the anaerobic contribution can supply up to 5% of the total energy production (Bergh, 1980). For distances of 30 kms, the anaerobic contribution can still represent a small but significant portion of the total energy production. This may be confirmed by moderately high blood lactate levels. Thus anaerobic energy transduction, while relatively less important than aerobic energy, may yet be decisive in terms of final results, primarily over shorter distances.

Table 3: Post-race Lactate Values (from Bergh, 1980)

10km		15km		30km'		30km'	
Time	Lactate	Time	Lactate	Time	Lactate	Time	Lactate
35.17	139	53.48	94	1.31.50	123	1.50.37	110
35.47	133	53.53	110	1.32.32	91	1.50.41	—
36.09	192	54.56	—	1.32.41	63	1.50.57	69
36.13	144	55.10	100	1.32.47	—	1.51.46	60
36.17	149	55.17	109	1.33.07	94	—	—
36.25	109	55.20	108	1.33.28	118	—	—
36.36	110	55.35	110	1.33.44	—	1.52.58	41
35.57	135	55.39	132	1.33.45	77	1.53.03	52
—	—	55.40	—	1.33.47	—	1.53.03	62

50km		85km	
Time	Lactate	Time	Lactate
3.06.42	39	5.01	—
3.10.30	42	5.06	19
3.10.38	47	6.28	33
3.11.42	59	7.08	22
3.12.12	25	7.50	15
3.14.31	38	8.30	26
3.14.31	31		
3.14.53	—		
3.15.20	—		

Note: Values are in mg%

Conversion: 1mM\L = 9 mg%

2.8 SKI TRAINING AND ANAEROBIC CAPACITY

The toleration of lactic acid accumulation, as opposed to increasing the glycolytic rate, is the major aim of the anaerobic training practiced by most ski racers, particularly in the pre-competition season. This, plus the fact that elite ski racers are characterized by very high oxygen uptake values and that they concentrate the majority of training on enhancing the aerobic system, implies that the training methods and effects will be different from those of athletes in more strictly anaerobic events. As a result of this training, it is likely that the athlete would be better able to metabolize the lactate in the muscle. See table 2 for details.

In view of the fact that the training adaptations for elite athletes are largely local, the need to train the muscles in similar patterns to the performance demands is emphasized.

Anaerobic training should focus on the same muscle groups as used for training and competition in order to promote muscle force production. The double poling method so commonly used in final sprints in the stadium is also gaining popularity in a modified form for use in the new technique of ski "skating". This technique is said to place greater emphasis on the upper body musculature and thus high force production capabilities of these muscles would be desirable for optimum performance. Komi (personal communications, 1986), has reported forces of between 1.6 and 2.5 times greater during the skating technique than during classic technique as measured with force transducers incorporated into ski poles. Rusko (1988) has presented data indicating higher lactate values

and respiratory exchange ratios obtained while skating as compared to using the "classic" technique at the same intensities. Thus the use of an ergometer which mimics a skill which is common to both techniques is advisable.

A current training device known as a roller board (see figure 7, page 59) emphasizes the development of force production in the upper body musculature through a similar range of motion (Saar P., Scheier A., personal communication) to that used in skiing. That Sharp and Koutedakis (1987) found that upper body exercise was more appropriate than lower body exercise for use in analyzing the anaerobic energy transduction in elite rowers, gymnasts and judoists, lends support to using an upper body exercise for the current study. The roller board thus lends itself to use as an ergometric tool for examining force production characteristics under anaerobic lactic conditions.

2.9 CONCLUSION

The production of force in athletic performance may be affected by a number of factors. These factors depend upon the specific exercise conditions, including duration, intensity, type of contractions, range of motion, and muscle groups used. Ski racing performance relies to a small but significant degree on intense short-term force production typical of the anaerobic lactic system. The fact that this anaerobic work is performed within the context of a largely aerobic sport implies a high level of aerobic conditioning, confirmed by high maximal uptake values, which can have significant effects on the metabolism of lactate and thus

force production. In order to determine the physiological capacity of an athlete to develop and maintain force under conditions of an anaerobic nature, the system should be isolated as much as possible, and the muscle groups should correspond to those used in training and competition.

III

METHODOLOGY

3.1 INTRODUCTION

This chapter will outline the subject population, exercise protocol, method of collection and analysis of force production, analysis and assay of blood lactate and the statistical design used in this study.

3.2 SUBJECTS

The subjects in this study were all members of the Canadian National teams for cross country skiing. These included both junior and senior, and male and female athletes. They represent a high aerobically fit group (see Table 4, following page) whose training includes a significant amount of upper body work. These athletes train year round, and the testing occurs at specific phases in training throughout the year. The athletes had been previously required to give their informed consent upon accepting national team status through the respective sport-governing association.

Table 4: Subjects Physiological and Performance Charactaristics

Subjects	Age (yrs)	Weight (kg)	VO2rel (ml/kg/min)	Competitive Level
Males				
ID=1	28	71.3	80.7	WCP, OT
2	24	67.6	72.1	OT
3	20	82.9	75.5	OT
4	20	82.9	70.0	OT
5	25	72.8	77.9	OT
6	19	71.2	74.0	NST
7	19	78.6	67.7	NST
8	18	78.4	63.5	NST
Means	21.6	75.7	72.7	
Females				
ID=9	22	55.9	67.6	WCP, OT
10	25	56.5	67.3	OT
11	21	67.9	59.8	OT
12	21	52.9	60.0	OT
13	26	60.6	63.6	WCP, OT
14	19	58.3	62.3	NST
15	18	47.8	59.3	NST
16	19	52.3	64.3	NST
17	18	50.6	59.9	NST
Means	21.0	55.9	62.5	

Note; NST=National Ski Team OT=Olympic Team WCP=World Cup Points acquired

3.3 GENERAL EXPERIMENTAL PROCEDURES

A battery of tests were performed by the athletes at regularly scheduled periods throughout the year at the University of Ottawa. Included among these tests was an intense two minute exercise using an ergonometric device known as a 'roller board'. All the athletes were familiarized with the test protocol prior to testing. All the athletes had had previous experience in the use of the roller board, and many had used a roller board regularly during pre-season strength training and so were familiar with the technique required. The technique used for this exercise involves minimal skill and it is felt that the results are likely to be the result of physiological responses as opposed to differences in technique.

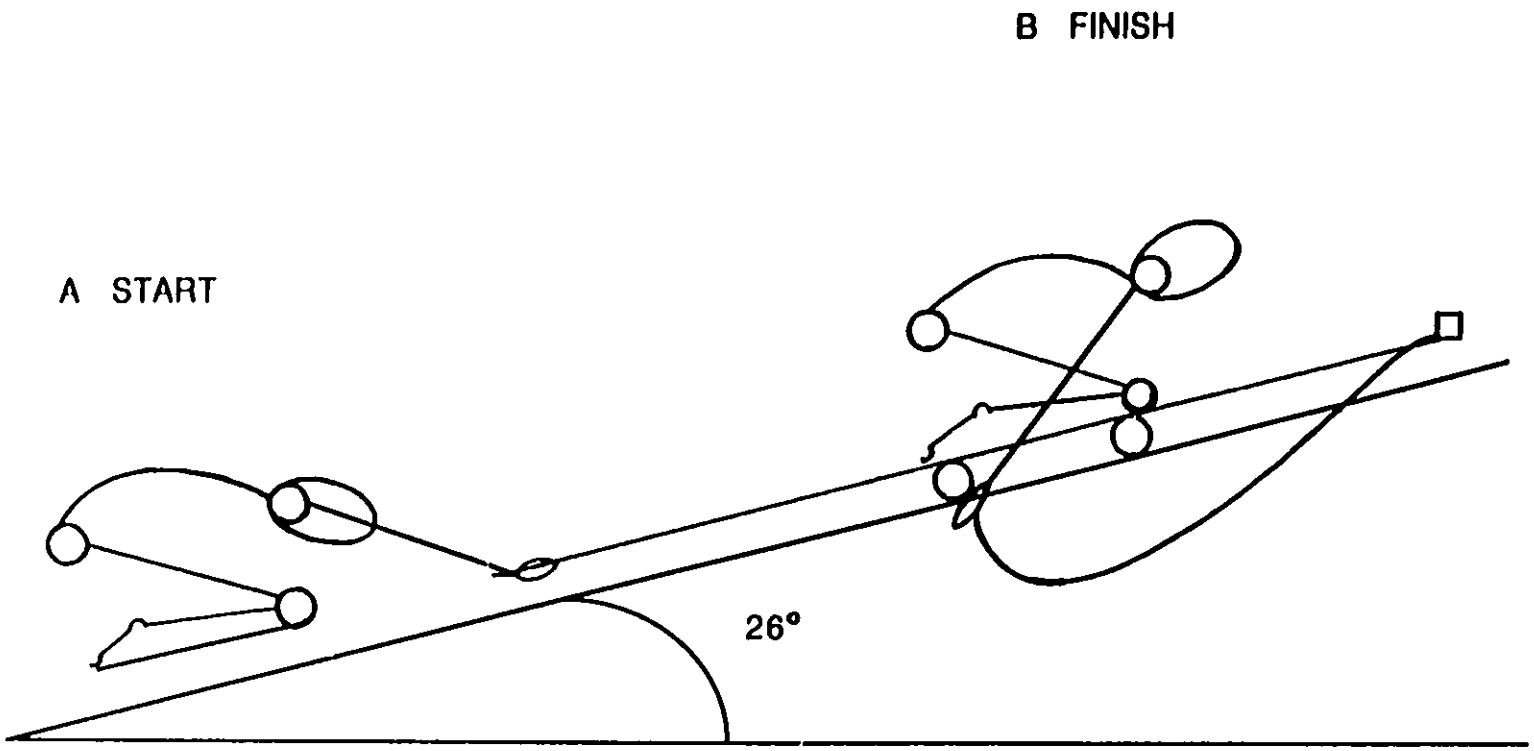
Each subject was required to repeat a simulated double-poling motion on this roller board using maximum effort at a rate of one 'pull' every 2.5 seconds according to the recommended method (Saar and Scheier 1985). In early testing sessions the cadence was set at a rate of one 'pull' every 3 seconds, but this rate was modified as a result of feedback from coaches and athletes regarding the simulation of the double poling 'tempo' on snow. Also pilot values indicated that the athlete's fitness levels had increased to the point such that fatigue was not apparent for many athletes within the test period using the three second protocol. No attempt was made to control either the distance travelled or the velocity of the movement. This test lasted for two minutes (or 48 pulls), after which fingertip blood samples were drawn and subsequently analyzed for lactate concentration. The test was performed not less than two

hours after previous testing to allow any earlier accumulation of lactic acid to be dispersed (Hultman and Sahlin, 1980). When the time between tests was close to two hours, a resting blood sample was taken to ensure that the blood lactic acid levels were consistent with normal resting levels (i.e. below 2mM of lactate). A warmup some minutes prior to testing using the specific muscles involved was strongly recommended to prevent injury.

A single pull of the double poling motion began with the subject kneeling on a board equipped with wheels. The board was then pulled by the subject up a 2.5 metre metal ramp set at an angle of 21.5 degrees for females and 26 degrees for males according to Saar and Scheier (1985) See Figure 6, page 59. The subject held onto the straps using a grip similar to that which they used for skiing, and allowed full body weight to rest on the straps with arms fully extended. On the starting signal the athlete pulled him/herself up the ramp by pulling against the straps. At the top of the stroke the arms were extended behind the torso. The subject then returned to the initial position. Each subject was advised to control the return so as to avoid too much eccentric contraction and subsequent muscle soreness.

A tape recording standardized the delivery of instructions and assisted the subject with maintaining the required rhythm. The subject was instructed to exert all-out effort for each individual pull, and to continue pulling at maximum force even when full extension could no longer be reached. The athletes were motivated to perform with verbal encouragement from the testers and fellow team members.

Figure 6: Rollerboard Simulated Double Poling



Note: 21.5°for women

3.4 MEASUREMENT OF FORCE PRODUCTION

After initial familiarization with the test procedure, each subject began by allowing full body weight to hang from the straps in order to partial out the effect of body weight on the force curve (see figures 6 and 8). No attempt was made to adjust for either body size or proportions.The force exerted by the weight and by the application of muscular effort was measured in the form of voltage changes via a load cell (Lebow Assoc. Inc., model 3132). This load cell was connected to a metal bar to which the straps were attached. Once the test began, the voltage changes were continually recorded, amplified by a bridge amplifier (Honeywell Inc., Accudata 218), and then were digitized using an Applescope Analog to Digital Converter (RC Electronics Ltd.) APL-2D system in conjunction with an Apple IIe computer system. The amplitude of the force curve was adjusted for males (A=0.2) and females (A=0.1) to allow as much information as possible to be seen on the screen for each athlete.

Calibrations of the recording apparatus were performed either immediately prior to, or immediately after the testing session using a plumb line suspension of known weights of up to 165 kgs for the males and 95 kgs for the females. Subsequent force values for each of the individual measurements were calculated using the linear regression equations derived from the calibration measures, and applying them to the recorded deflections (see figure 8, page 61).

Figure 7: Schematic Diagram of the Recording Apparatus

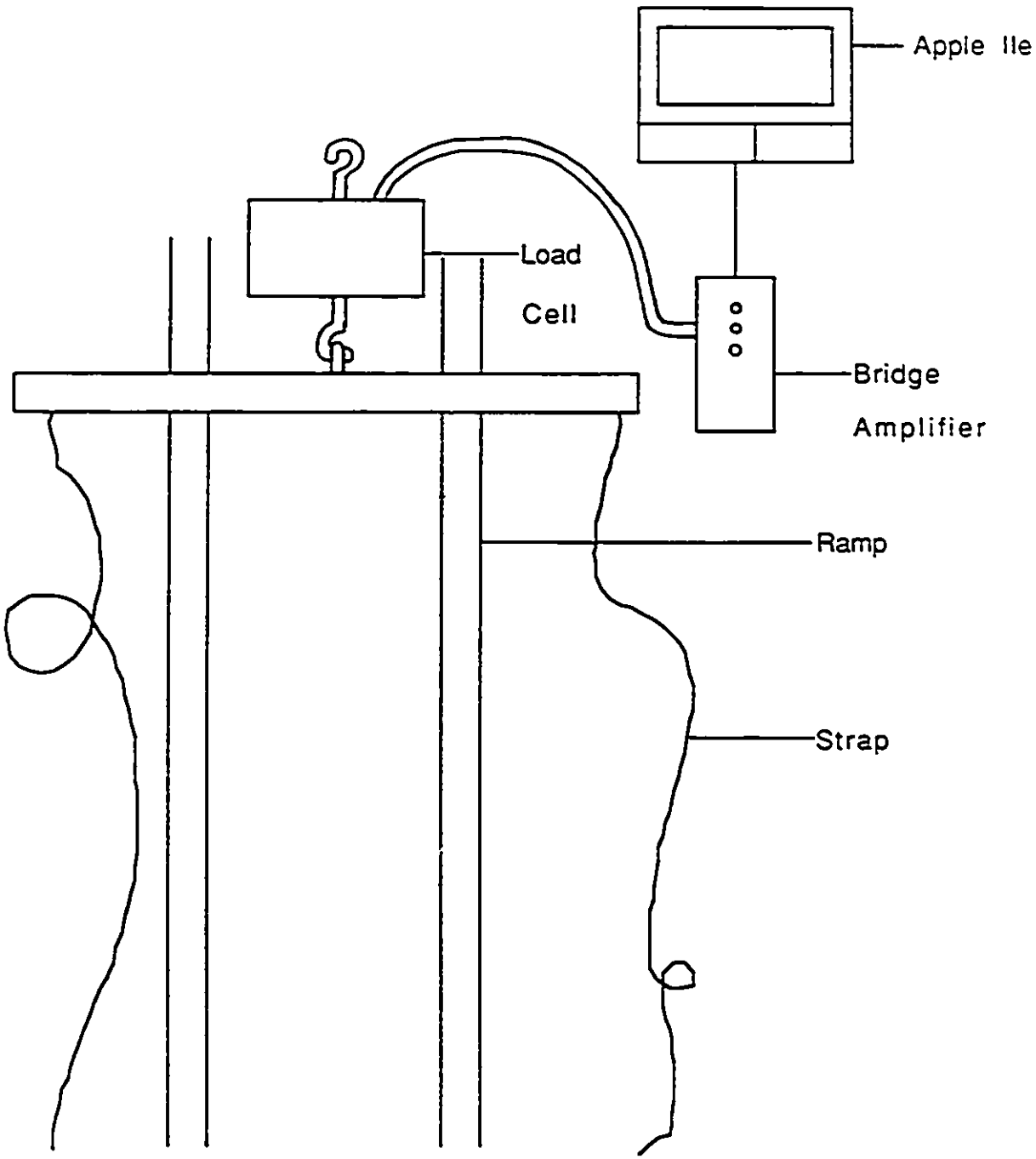
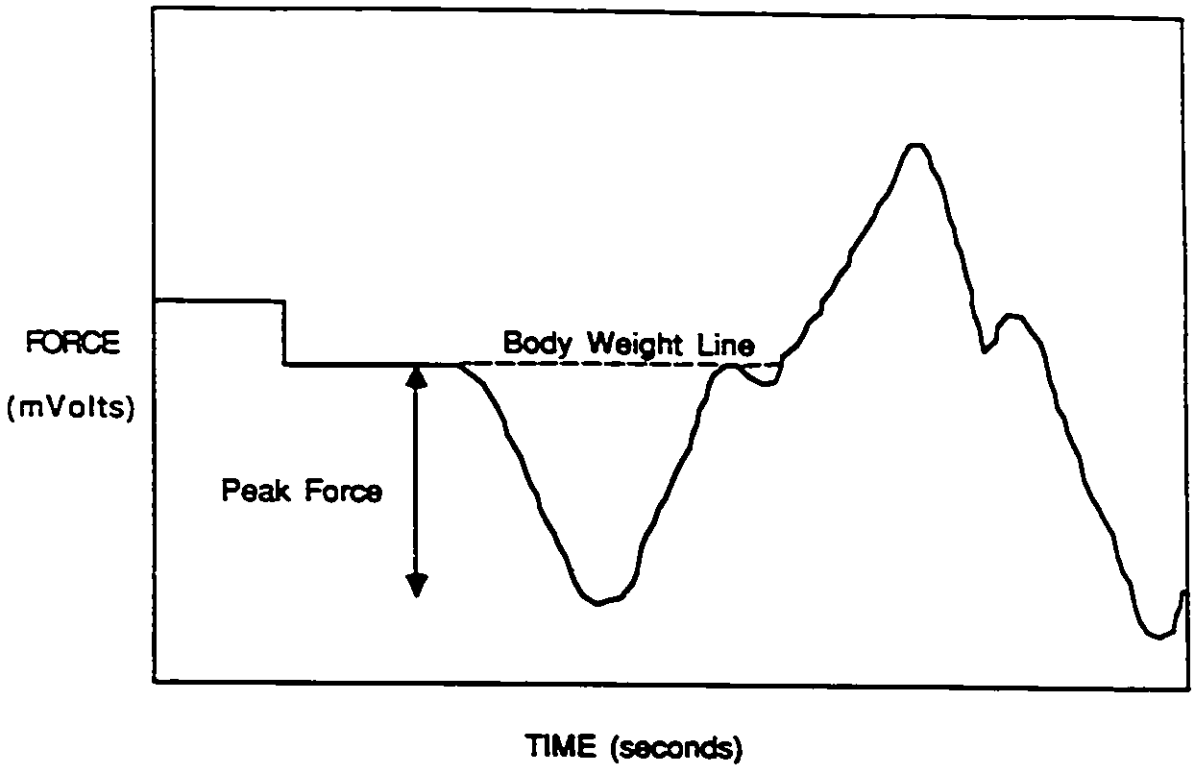


Figure 8: Typical Force Curve and Method of Analysis



Prior to analyzing individual movement curves, the body weight deflection was determined and this value was then used as a baseline reading upon which to measure the individual peak force values (see Figure 8). A video tape recording of the test was used in analyzing those curves which seemed to be altered by abnormal or excessive body movements. For example, occasional uncontrolled drops of body weight onto to the straps at the bottom of the ramp resulted in either a very sharp steep peak or a double peak. In such cases the second peak was taken to represent the peak force actually used to pull the subject up the ramp. The deflections, measured in millivolts, for each pull were translated into Newtons of force using the regression equations from the calibration. This information was then plotted on a graph depicting force (Newtons) against time (seconds). The graph was then analyzed to determine the time to drop-off, the degree of drop-off, and the pattern of force decline (i.e. muscle fatigue). The force and fatigue indicators were calculated in the following manner;

Peak force: the highest force value recorded for the athlete.

Mean force: the mean value for all the pulls throughout the exercise.

TDO: the recorded time when the force measures were consistently lower than the lowest of the early peak values.

DO-Index: the difference in Newtons between the mean of the force values recorded from 5 to 15 seconds and the mean of the values recorded from 105 to 115 seconds.

M-Index: The difference between the mean level of force before drop-off had occurred and after drop-off (maintenance of force index). This is expressed as a percentage.

3.4.1 Analysis of Blood Lactate

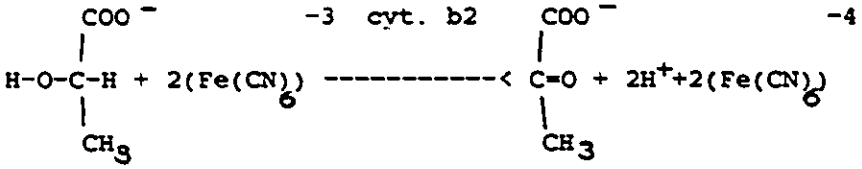
Once the two minute test was completed, the athlete was assisted from the rollerboard and into a chair. The fingertip was cleaned with alcohol and allowed to dry before lancing for each sample to avoid contamination of the sample. Once the sample was drawn, by capillary action into a heparinized tube, exactly 20 uL of blood were then transferred from the capillary tube and immediately haemolysed with 380 uL of diluting solution. Once haemolysed and firmly sealed, the samples potentially remain stable for another 48 hours (Kontron Medical, 1981). However, all samples were analyzed within a period of five hours. These samples were taken at two and three minutes post-test as a result of; a) earlier pilot work indicating that values dropped for this population beyond three minutes (see appendix D), and b) data from Medbo and Sejersted (1985) demonstrating peak blood lactate values occurring at post three minutes or earlier for elite cross country skiers following an all-out one minute treadmill run. As well, recent (unpublished) data from National ski team members have indicated peak lactate values occurring within three minutes post-exercise for and post-race sampling (La-p0 = 11.11, La-p3 = 9.96). Values after maximal VO2 testing showed the same trend (La-p2 = 8.40, La-p3 = 7.61).

3.4.2 Lactate Assay

Blood lactate concentration was determined within five hours of sampling time using a Kontron Medical 640 Lactate Analyzer (Roche Bio-Electronics).

This method involves:

a) the enzymatic oxidization of lactate to pyruvate in the presence of cytochrome b2:



and b) the electrochemical oxidation of the hexocyanoferrate II formed:

The two electrons released for each lactate molecule oxidized cause a current to develop. The linear relationship between the current developed and the lactate concentration is achieved by first order kinetics of the enzymatic reaction.

3.5 STATISTICAL ANALYSES

3.5.1 Descriptive

Initially, descriptive analyzes were performed to provide means and standard deviations for all the force and lactate values (the dependent variables) as well as selected physiological measures. The graphs of force versus time were analyzed to determine the time to drop-off, from which the other values (for definitions see page 10) were determined.

3.5.2 Correlations

A general linear models (GLM) procedure was performed followed by a Scheffe post-hoc analysis to determine the significance of difference between male and female groups for all of the dependent variables. In order to determine whether there were any relationships between the force variables and the lactate variables, a correlational matrix was used to compare all of the dependent variables. This was performed for each of the male, female and pooled data.

IV

RESULTS

4.1 INTRODUCTION

The purpose of this study was to examine the relationship between force production characteristics and blood lactate in elite cross country male and female skiers. Of particular interest were the relationships between the fatigue indicators as derived from the force analysis, and the relationship of these values to peak post-exercise lactate values.

Force values from seventeen National ski team members, nine females and eight males, were obtained throughout a two minute intense exercise. Lactate samples were taken at two and three minutes post exercise. The fatigue indicators derived from the force values included the following:

a) time to drop-off (TDO)

b) peak force value recorded during the exercise (F-Peak)

c) mean force value calculated from the average of all 48 pulls during the exercise (F-Mean)

d) drop-off index (Newtons) as defined by DO-Index = (a-b)
where:

a = mean of initial values from five to 15 seconds

b = mean of final values from 105 to 115 seconds

e) maintenance index (Newtons) as defined by M-Index = B/A x 100

where;

A = average of all values prior to drop-off (TDO)

B = average of all values after drop-off

This chapter presents first the descriptive statistics for male and female athletes for the dependent variables (as defined on page 10). The rationale for separating the data on the basis of gender is discussed, and the correlational statistics for males and females are presented. The final section examines the meaning of these results and compares them with previous literature.

4.2 SUBJECT'S PHYSICAL CHARACTERISTICS

The subjects of this study (see Table 4, page 55) consisted of eight female and nine male members of the National Cross Country Ski Team, ranging in age from 18 to 28 years. They were all highly aerobically fit athletes, with maximal VO2 values ranging from 59.3 ml/kg/min to 80.4 ml/kg/min (mean=67.6 ml/kg/min). Ten athletes qualified for the Olympic Games in 1988. Among these, three had earned World Cup points by having placed in the top 15 internationally. A considerable range was found in body weight (47.8 kg to 82.9 kg), as may be expected when males and females are grouped.

4.3 RESULTS OF DESCRIPTIVE ANALYSIS

The results of the descriptive analysis describe a subject group with a mean age of 21 years and with a weight difference of approximately 20 kilograms between the males and the females. This substantial difference in weight reinforces the appropriateness of including a weight baseline measure to compensate for the discrepancy. To further substantiate this, a correlational matrix was generated for body weight with the other dependent variables (see Appendix B). The lack of significant correlations for body weight with any force or lactate variables would imply that the weight baseline measures were effective.

The post-exercise lactate values were elevated and showed little change from the second minute to the third. The results for the force values and fatigue indicators described a general pattern for the subjects. A relatively high amount of force was generated initially and was maintained for approximately 70 seconds of a 120 second exercise. The absolute force values tended to be higher for the men than the women, although the ability to maintain force, or resist fatigue, was similar. Once fatigue had occurred, the force values dropped off to levels representing, on average, 73% (M-Index) of the mean values prior to drop-off. The absolute amount of drop-off was greater for the males than the females, but when expressed relative to the initial peak values, the difference was less.

These results are summarized on Table 5, page 69, and in Figure 9, page 71).

Table 5: Descriptive Statistics for Men and Women

Variable	M N	W N	M Mean	W Mean	M STD	W STD
TDO (seconds)	8	9	70.1	68.1	28.2	18.1
F-Peak (Newtons)	8	9	564.0	462.0	116.0	107.0
F-Mean (Newtons)	8	9	379.0	339.0	65.0	105.0
DO-Index (Newtons)	8	9	199.0	163.0	132.0	49.0
M-Index	8	9	74.0%	72.2%	19.0	11.0
La-p2 (mM/L)	8	9	8.87	7.69	1.69	1.27
La-p3 (mM/L)	8	9	8.50	7.72	1.41	1.21
VO2rel (ml-kg-min	8	9	72.7	62.5	5.6	3.5
Age (years)	8	9	21.6	21.0	3.6	2.9
Weight (kgs)	8	9	75.7	55.9	5.8	6.0

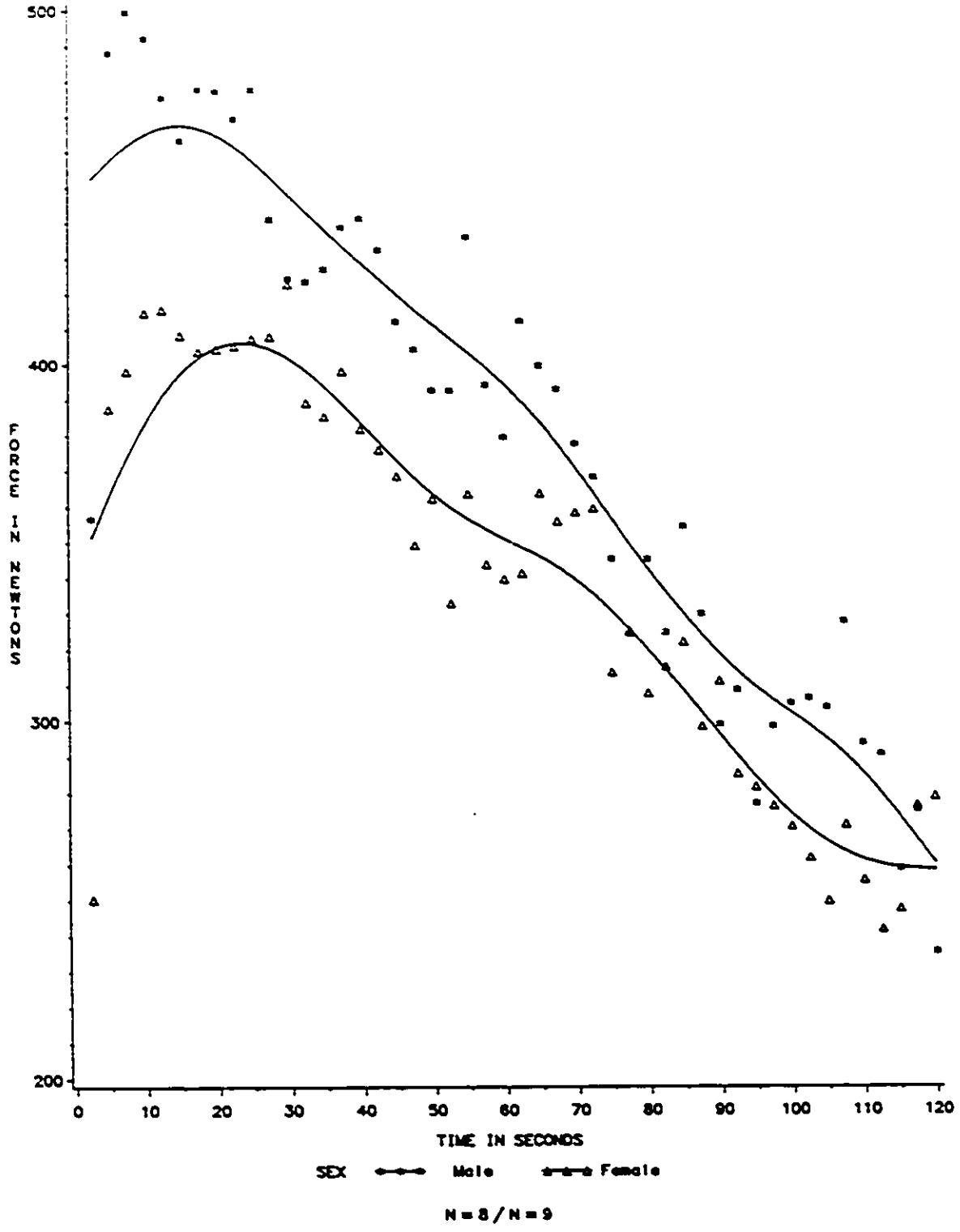
See page 10 for variable definitions

The mean values for the variables which were calculated on the basis of an individual's relative response - such as time to drop-off and M-Index - were quite similar for males and females. Those variables which were calculated solely according to absolute values showed greater variation.

The mean TDO values (70.3 seconds and 68.0 seconds for males and females respectively), although longer than many of those reported in the literature, showed little difference between the genders and were within the range of expected values for a supramaximal exercise. Katch and Weltman (1979), report a 42 second drop-off point for maximal cycling by physical education students. Hultman et.al., (1982) report a 55 second drop-off, and many tests (Bouchard et.al., 1982; Fujistuka et.al., 1982; Thomson and Garvie, 1981) use a maximal treadmill exercise designed to cause exhaustion at approximately 60 seconds. The peak force measures were difficult to compare directly with the literature, as no similar test measuring force for a similar mode of exercise had been found by this author. Ekstrom (1981) reported a maximum value of 210 Newtons of force per pole during double poling, but these values were recorded under very different conditions from those of the current study.

It was expected that the force values would be higher in men than women, due to higher reported strength capacities for men (O'Bryant, 1985; Astrand and Rodahl, 1977); as demonstrated in these results (see figure 9, following page).

FIGURE 9 :MEAN ROLLERBOARD FORCE VALUES
FOR MEN AND WOMEN



However, care must be taken in interpreting these results, and any of the mean force data, due to large standard deviation values for both males and females (see figures 10 and 11, pages 73 and 74 respectively). These results indicate a substantial difference in the ability to produce peak and mean forces among individual cross country skiers, regardless of gender.

The mean DO-Index values followed similar trends to the F-Peak values with respect to the gender differences, as might be expected since these also are representative of absolute values. The standard deviations demonstrated a large degree of variation in results, although this spread was unexpectedly less for males. The standard deviation values for the F-Mean variable were much lower for females than males (48.8 vs 132.5), although this may in part be explained by the females' lower relative force output.

Studies using similar techniques for measuring the degree of drop-off (DO-Index) in a short term maximal exercise, expressed the amount of drop-off as a percentage of the peak values. In order to compare the literature values to those in the current study, these were also converted to similar units. For both the men and the women in the current study, the percentage of drop-off was 35.3%. This was lower than many previous studies which reported values of 50% (Komi and Rusko, 1974), 57% (Tesch, 1978) 59.7% (Katch, 1973) and 68.5% (Katch and Weltman, 1979).

FIGURE 10:MEAN ROLLERBOARD FORCE VALUES WITH STANDARD DEVIATIONS

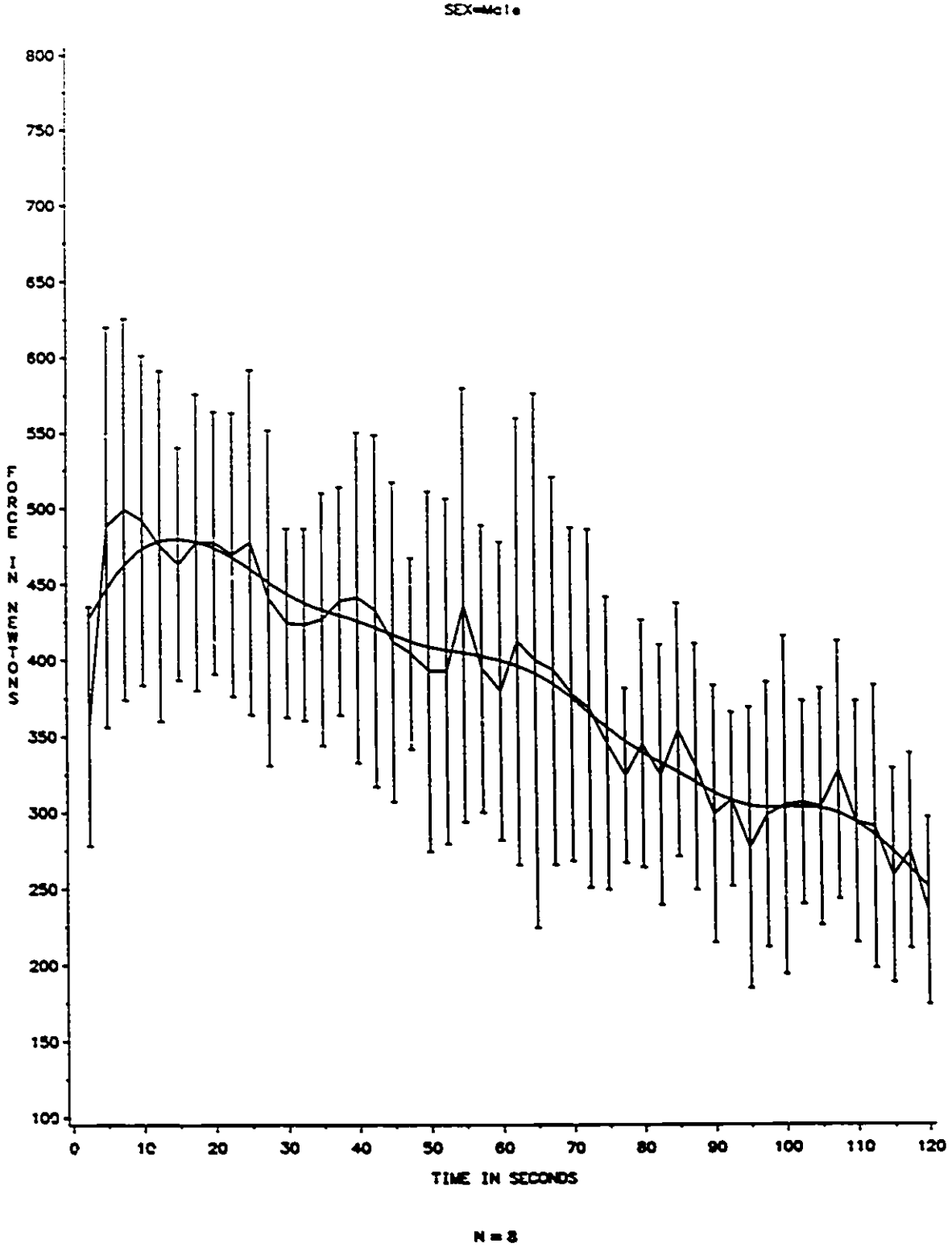
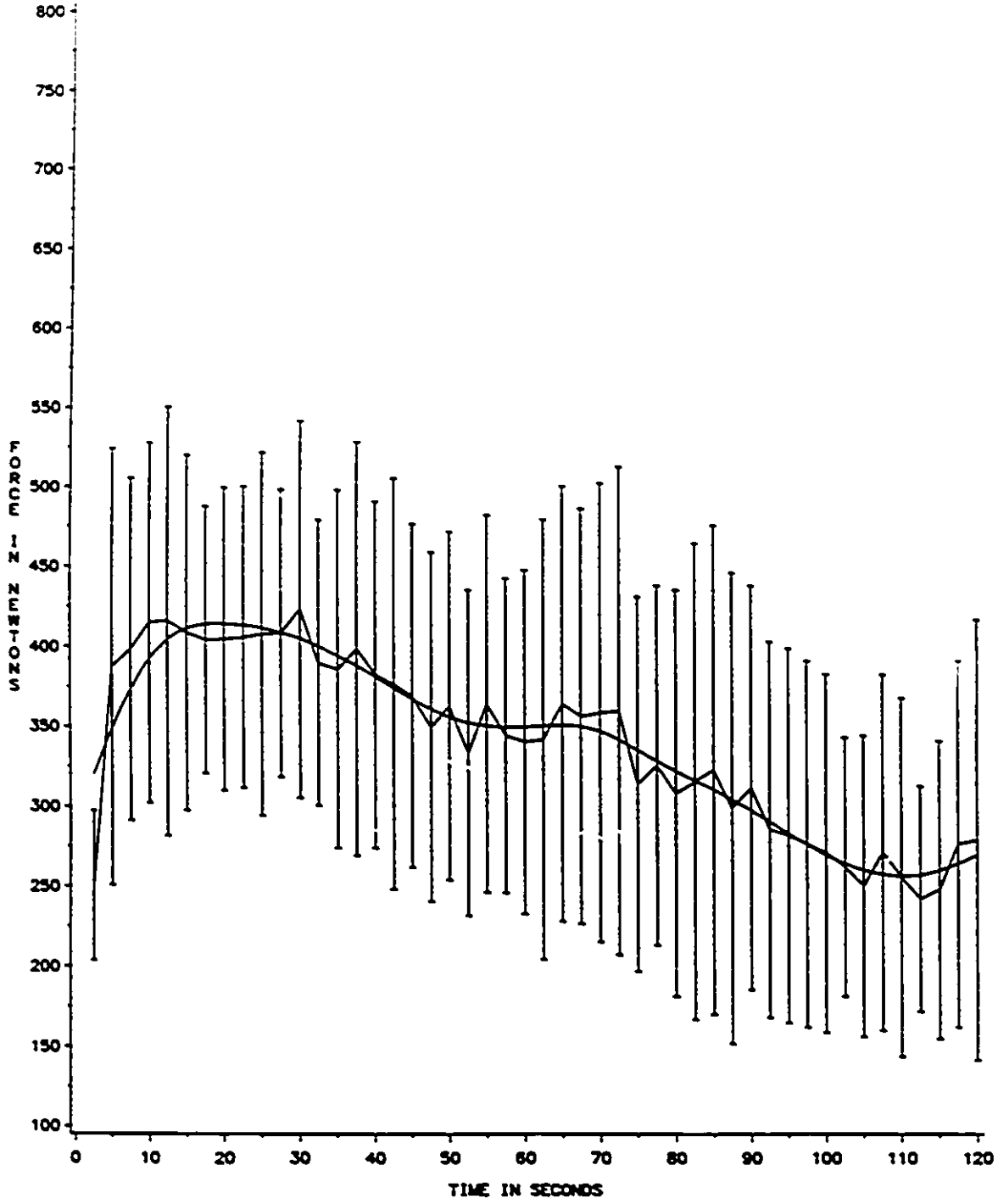


FIGURE 11: MEAN ROLLERBOARD FORCE VALUES WITH STANDARD DEVIATIONS

SEX=Female



N = 9

It is suggested that some of the differences may be accounted for by the methodological variations in:

a) the intensity and/or duration of the exercise

b) the ergonometric devices used, and, as a result, differences in the use of muscle groups and types of contractions

c) the actual units measured

Moreover, these discrepancies may be related to the unique qualities of the subject group, and to the potential differences in ability to metabolize lactate, as suggested in Chapter 2 (see Table 2, page 47). A hypothetical superior ability to metabolize lactate would be expected to result in lower post-exercise lactate values, such as those seen in this study. Since these lower values might be accompanied by a lessening of those fluctuations in pH levels which affect glycolytic flux and/or the functioning of the contractile apparatus, the ultimate result of an enhanced ability to metabolize lactate should be a reduced fatigue response. The M-Index values of 74% and 72.2% , which indicated the degree to which the force output could be maintained after drop-off had occurred, could not be directly compared to previous studies.

Vandewalle et.al., (1987) suggested that athletes with low anaerobic power but with high aerobic power, as seen in the current study, and a short oxygen transient should contribute a higher percentage of energy via the aerobic system at the end of an all-out exercise than should power athletes. Other researchers have also explained their results on

this basis, including Goslin and Graham (1985) and McCartney et.al., (1983), who found that aerobic power, as indicated by maximal VO2 values, was negatively related to the rate of power decrease. However, no such correlation was found in the current study.

The lactate values were slightly higher for males (8.87 vs. 7.69) as compared to females. Although this was not statistically significant, the significance may be considered borderline at $p < 0.11$. The higher values for men may have been due to larger muscle mass, and thus a potentially greater ability to produce lactate. This is in agreement with the findings of Astrand et.al., (1986) who also found higher peak blood lactate values for males as compared to females after supramaximal arm and leg work.

The values in the current study were considerably lower than those reported by Ohkuwa et.al., 1984, (19.06 mM/L) and by Medbo and Sejersted 1984 (16.7 mM/L) for sprint trained and untrained subjects. They were somewhat lower than those reported by Ohkuwa et.al., (1984) for distance runners (14.97 mM/L), and by Fujitsuka et.al., (1982) for untrained subjects (12.98 mM/l). They were slightly lower than those found by Medbo and Sejersted (1985) for Norwegian elite skiers (12.5 mM/l). These previous results were measured after maximal leg exercise. However the results were similar to those reported by Kindermann and Keul (1977) for elite skiers after a ten km ski race (6.0-9.2 mM/L), and for Secher et.al, (1974) after maximal arm cranking (8.6mM/L). They were slightly lower than those reported by Komi and coworkers (1977) for Finnish elite skiers (11.2 mM/L), and by Bergh et.al, (1976) after maximal arm pedall-

ing (12.1 mM/L). Kindermann and Keul et.al, (1977) also found that the blood lactate values for elite endurance athletes (taken within 10 minutes of international competition) resulted in generally lower values when compared to athletes in more traditional anaerobic sports.

The two minute post-exercise lactate values were not very different from the three minute values. Pilot work with this group had indicated that beyond three minutes, no further positive increments in blood lactate were observed. This was contrary to a number of studies which reported peak blood lactates that occurred somewhat later. Fujitsuka and coworkers (1982), reported peak post-exercise lactate values occurring at approximately 7.6 minutes post-exercise for untrained subjects, Thomson and Garvie (1981) at five minutes for marathon runners. However, Komi and coworkers (1977) found peak values occurring at three to five minutes for elite athletes. The results of the current study are consistent with the work of Medbo and Sejersted (19[illegible]) who observed peak values at three minutes post-exercise for elite Norwegian skiers.

The maximal VO2rel values were high, with the variations non-significant, indicating a fairly homogeneous population within each gender grouping. The mean VO2 values are higher than those reported for college level skiers (Kindermann et.al., 1979) and for competitive sub-elite skiers (Saar, 1986) but comparable to those reported for elite skiers (Rusko et.al., 1978, Medbo and Sejersted, 1985) and slightly lower than those reported for international elite skiers (Bergh, 1982; as cited in Scheier, 1983). The difference between males and females was consistent with the literature (Astrand and Rodahl, 1977; Boulay et.al.,

1985) which indicates that women generally have maximal oxygen uptake values which are approximately 80% of those for men.

These results indicate a high aerobically fit group with maximal VO2 values comparable to other elite cross country skiers. They demonstrate, on average, a relatively low degree of drop-off as well as the ability to produce force at consistently high levels for a long period before fatigue, as indicated by the TDO fatigue indicator, is reached. These athletes demonstrate a similar time course for peak lactate levels to appear when compared with other elite skiers, but a slightly shorter time course than other endurance athletes, and a considerably shorter time than untrained or sprint trained athletes. The differences between the genders were consistent with the literature with regard to VO2 values and peak force values.

4.4 CORRELATIONS

The purpose of the study was to investigate the relationship between lactate and force production among male and female cross country skiers. Since the significance testing (see page 89) showed three of the variables to be significantly different between males and females, a decision to examine separately the correlations between the force and lactate values for each gender was made. A correlational matrix was calculated for the pooled data (see appendix B) but most of the significance showed in the gender-segregated correlations. A detailed description of the correlational results for each gender will now be presented.

The results of the correlation matrix are presented in tables 6 (page 80) and 7 (page 81) for males and females, respectively. For both the men and the women, the peak force values were found to have a significant correlation with the average force values ($r=0.73$, $p < 0.01$ and $r=0.98$, $p < 0.01$ respectively). This might be expected since the F-Peak values reflect force generating capacity and the peak values would be incorporated in the F-Mean calculations, regardless of the subsequent fatigue pattern. However, the relationship between these variables is much tighter for the women, who had a coefficient of variation of $r2=0.95$. This implies that the degree of variation in F-Mean values can be largely accounted for by the variation in F-Peak values, and that there may be a difference in the interaction of these two variables between the genders.

The second common correlation was found between the La-p2 samples and the La-p3 values. The coefficient of variance was very high and the probability was significant. This was reasonable to expect since the average values (see Table 5) showed little difference , and the difference was generally in the same direction such that the La-p3 values tended to be slightly lower than the La-p2 values.

A correlation which was somewhat similar for both genders was that of the F-Peak and DO-Index variables. The correlation coefficient is quite strong for men, and significant at the $p < 0.01$ level. There was, however, only a moderate correlation for women, and the significance was only at the $p < 0.08$ level. This suggests that there is a relationship between the peak force production and the degree of drop-off in men, and

Table 6: Correlational Matrix for Males

Pearson Correlation Coefficients / Probability Statements/ N=8

	TDO	F-Peak	F-Mean	DO-Index	M-Index	La-p2	La-p3	VO2rel
TDO	-							
F-Peak	-.249 .551	-						
F-Mean	.196 .642	.729* .040	-					
DO-Index	-.636+ .090	.849** .008	.354 .390	-				
M-Index	.761* .028	.704+ .051	-.299 .471	-.886** .003	-			
La-p2	-.021 .960	-.098 .817	.211 .616	-.269 .519	-123. .772	-		
La-p3	.019 .964	-.077 .857	.261 532	-.263 .530	-.125 .768	.990** .0001	-	
VO2rel	.416 .305	-.001 .998	-.004 .992	-.107 .801	.510 .197	-.785* .021	.806* .016	-

\+ Significant at the p > 0.10 level

* Significant at the p > 0.05 level

** Significant at the p > 0.01 level

See page 10 for variable definitions

Table 7: Correlational Matrix for Females

Pearson Correlation Coefficients | Probability Statements \ N=9

	TDO	F-Peak	F-Mean	DO-Index	M-Index	La-p2	La-p3	VO2rel
TDO	-							
F-Peak	.664+	-						
	.051							
F-Mean	.756*	.977**	-					
	.018	.0001						
DO-Index	.166	.604+	.482	-				
	.670	.085	.189					
M-Index	.299	.301	.415	-.482	-			
	.434	.430	.267	.189				
La-p2	.642+	.692*	.698*	.187	.260	-		
	.062	.039	.036	.629	.498			
La-p3	.642+	.537	.573	.146	.066	.928**	-	
	.062	.136	.107	.707	.865	.0003		
VO2rel	.090	.413	.424	.116	.574	.012	-.187	-
	.819	.270	.255	.766	.106	.976	.630	

+ Significant at the p > 0.10 level

* Significant at the p > 0.05 level

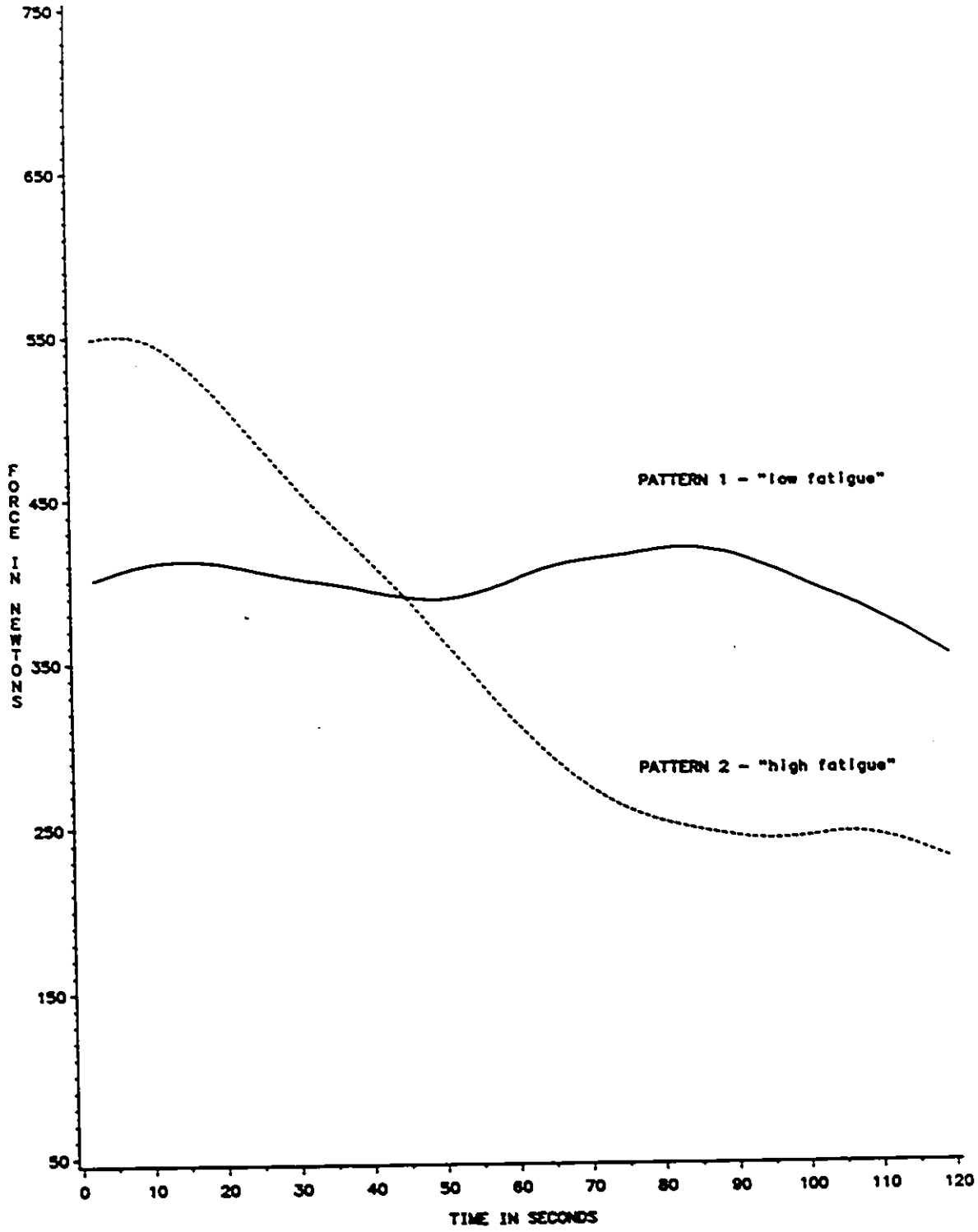
** Significant at the p > 0.01 level

See page 10 for variable definitions

perhaps also in women such that those who could produce the higher forces tended to fatigue the most. This also suggests that there may be a difference in the extent of interaction between the degree of drop-off and peak force between males and females.

Not all of the force and fatigue measures showed similar trends for both genders. For the men, a strong correlation ($r=0.77$; $p < 0.03$) was found between the TDO and the M-Index values. This suggests a positive relationship between the length of time that fatigue can be resisted and the degree of fatigue resistance (ie between when and how much they fatigue). In contrast, the correlation coefficient for the women was very low and non-significant. There is also a moderate negative correlation ($r=-0.64$) between the TDO values and the DO-Index values for the men, which was significant only at the $p < 0.06$ level. This relationship between the time at which fatigue occurs and degree of fatigue in absolute terms appears reasonable since this would tend to support the previously mentioned relationship between the TDO and the M-Index. These relationships are consistent with two possible patterns; one which describes a short time to fatigue (TDO) and a large amount of drop-off (DO-Index), as compared to a second pattern describing a long time to fatigue and a small amount of drop-off. These possible patterns are supported by the positive relationship between F-Peak and DO-Index as described on page 81. Similar confirmation is found in the negative relationship between F-Peak and M-Index. These correlations give us a picture of curves consistent with those shown in Figure 12 (page 83). Pattern 1, the "low fatigue curve", shows a relatively low peak force, (F-Peak), a long time

FIGURE 12:INDIVIDUAL FATIGUE PATTERNS
AMONG DIFFERENT MALE CROSS-COUNTRY SKIERS

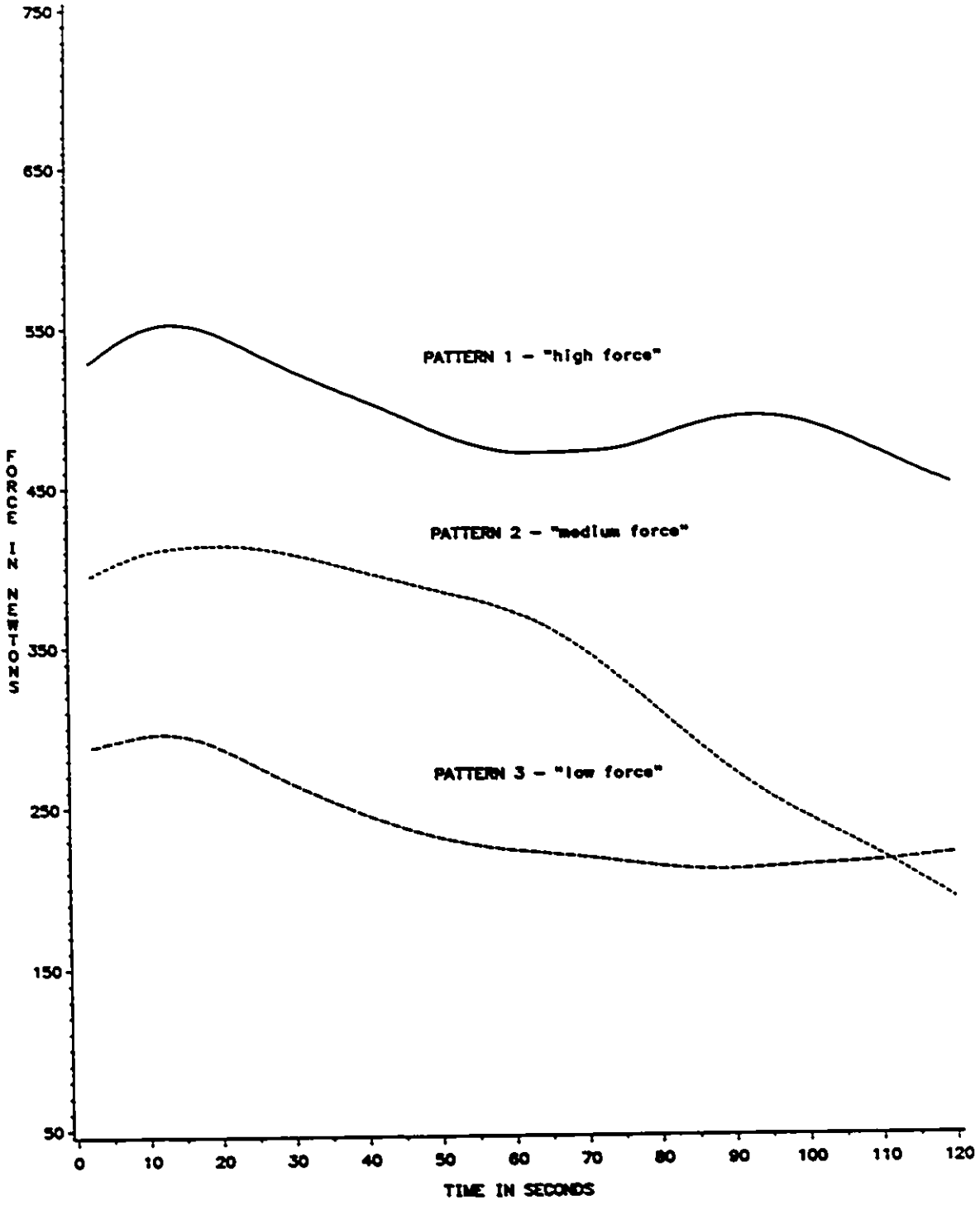


to drop-off, a small amount of drop-off and a high force maintenance (M-Index). Pattern 2, or "high fatigue", on the other hand, shows a high peak force, large amount of drop-off, short time to fatigue, and lower force maintenance. These relationships are again not seen for the females.

A strong negative relationship was found between the DO-Index and the M-Index values for men. This is not surprising, since a large absolute amount of drop-off does not seem compatible with a high ability to maintain force. Once again, no such relationship was found for the women. This is consistent with the pattern of results found for the men and not for the women and suggests a distinct difference in the fatigue response between the genders.

Among the women, the TDO variable was found to have a strong correlation with the F-Mean variable (r=0.76) and a moderate correlation with the F-Peak variable (r=0.66). These correlation coefficients are consistent with the correlation between the F-Peak and F-Mean variables, and suggest a single pattern, which is illustrated in Figure 13, page 85. These individual patterns show similar fatigue responses which vary according to the ability to produce peak force, such that those who produce low initial forces show curves which are similar in pattern to those who produce high forces, but with a downward and left shift for the weaker skiers. Clarkson et.al., (1984) found a similar consistency in fatigue patterns for elite oarswomen. They examined isokinetic fatigue curves of both oarswomen and untrained female subjects, and found that while the ability to produce tension varied greatly, the fatigue

FIGURE 13:INDIVIDUAL FATIGUE PATTERNS AMONG DIFFERENT FEMALE CROSS COUNTRY SKIERS



curves were very similar. This was true both among and between the groups.

For the women in this study, correlations were found between both the F-Peak and F-Mean values (r=0.69 and r=0.70 respectively) with the La-p2 values. This suggests a positive relationship between force production and peak lactate production capabilities, and is again consistent with the relationship between the F-Peak and F-Mean variables. Somewhat lower and less significant relationships were found between these variables and the La-p3 variables. These relationships were not observed for the men.

A correlation of r=0.64 ($p < 0.06$) was found between the TDO and both La-p2 and La-p3 values for the women. This suggests that, contrary to traditional belief, the ability to resist fatigue for these subjects may be associated with a high post-exercise lactate. No relationships between the above variables were seen for the men. Graphic illustrations of these latter three correlations may be found in Appendix C.

Another finding was the significant, negative degree of correlation between the maximal VO2rel variable and both the La-p2 and La-p3 variables for the men, and the lack of any such relationship for the women. The slightly lower coefficient and degree of significance for the La-p3 variable may be attributed to the slightly lower values for the mean La-p3 measures. This suggests that for this group of high aerobically fit male athletes, the degree of aerobic power may be somehow related to the ability to produce less lactate, and/or to metabolize it more efficiently. That this relationship is not seen for the women reinforces

the idea of a somewhat different fatigue response, although this response may be connected to the lower mean VO2rel values (62.5 ml/kg/min vs. 72.7 ml/kg/min) and/or the slightly lower lactate values found for these women.

Due to the small sample sizes, and moderate degree of correlation and/or significance in certain relationships, further investigation of these relationships is recommended. Also, the degree of variation in the force values (see figures 9 and 10) is quite high, and because the sample size is quite small, some patterns may have been obscured.

In summary, it appears that the nature of the fatigue response is fundamentally different for the male and female skiers. There may be two fatigue responses for the males; one associated with a lower peak force output, but with a greater degree of resistance to fatigue (Pattern 1, Figure 12); and the other one associated with a high peak force output, a short time to fatigue and a greater degree of fatigue (Pattern 2, Figure 12). The men also demonstrated a strong negative association between aerobic fitness, as indicated by the VO2 values, and blood lactate.

The women on the other hand, have demonstrated a non-traditional relationship between the strength and fatigue indicators, and also between fatigue and blood lactate. The force fatigue response for women seems to follow a pattern characterized by (for example) high peak force values being repeated fairly consistently for a relatively long period of time (i.e. high peak, high M-Index, long TDO) which may be followed by a large amount of drop-off (DO-Index) near the end. See Figure 13.

4.5 GENERAL LINEAR MODELS PROCEDURE AND SCHEFFE

The General Linear Models (GLM) procedure was used to analyze the variance between the genders for these groups instead of an ANOVA because of the different cell sizes (i.e. unbalanced design). The GLM procedure performs an analysis of variance using a linear model to predict the response as a linear function of parameters and design variables. The Scheffe post hoc analysis was used to analyze all significant main effect means found as a result of the GML analysis.

The results are presented in table 8 on the following page. Because three variables (F-Peak, VO2rel, and weight) were found to be significantly different, it was decided to run separate correlations for each gender independently as well as one for pooled data. See appendix B. Many of the coefficients showed different relationships between the variables for men and women, suggesting potential differences in both the fatigue response, and in the relationships between force production and blood lactate for the genders.

Table 8: GLM Procedure For Significance of Differences in Dependent Variables between Males and Females

Dependent Variable	df	Mean Square	F ratio	Probability
TDO (seconds)	1	21.57	.04	0.85
F-Peak (Newtons)	1	44614.11	3.59	0.078 *
F-Mean (Newtons)	1	6752.21	0.85	0.37
DO-Index(Newtons)	1	5318.33	0.56	0.47
M-Index (percent)	1	.0015	0.07	0.80
La-p2 (mM\L)	1	5.90	2.83	0.11
La-p3 (mM\L)	1	3.26	1.91	0.19
VO2rel (ml\kg\min)	1	421.30	20.81	0.0004 ***

* Difference is significant at the p > 0.10 level

*** Difference is significant at the p .> 0.001 level

GLM=General linear models procedure for ANOVA with different cell sizes.

See page 10 for variable definitions

4.6 DISCUSSION

The purpose of this study was to investigate the relationship between force and blood lactate in elite cross country skiers. The significant differences found in the GLM analysis and the differences in correlations for the males and females indicated that the results should be analyzed for each gender individually. Since high aerobic capacity is a variable which characterizes these athletes as a group, it was decided to include this variable in the correlations to determine whether it was indeed a factor which might influence the other variables or the relationships between them.

Not surprisingly, the results from Table 6 indicate that the F-Peak and F-Mean values, which both reflect absolute force output, were significantly correlated ($r=0.73$; $p < 0.01$). This is consistent with Goslin and Graham (1985), who found a strong correlation ($r=0.97$, $p < 0.01$) between peak and mean power for a 30 second Wingate test. It is not surprising that there would be a positive relationship between these variables, but it does not necessarily follow that the correlation would be high, since the pattern of fatigue will obviously influence the relationship. Perhaps the relative consistency in the fatigue pattern for women may help to explain the tighter relationship between F-Peak and F-Mean for women.

The strong relationship between the peak values and the absolute amount of drop-off in force for the men is consistent with much of the literature which examines the relationship between muscle metabolic properties and force, power or torque output during a short-term intense

effort. Bar-Or et.al., (1980) found that male subjects showed a high positive correlation between the percentage of FT fibres and each of average power, peak power and power decrease during maximal cycling. Edgerton et.al., (1983) reported that the time to exhaustion may be expected to decrease with increasing FT percentage. Tesch et.al., (1983) confirmed these results in a study of the relationships between FT/ST percentage and peak torque, fatigue, and LDH type and activity in male subjects during a one minute fatigue test. Positive relationships were found between both of the peak torque and torque decline variables ($r=0.86$, $p < 0.001$; $r=0.79$, $p < 0.001$) with FT percentages. Torque decline (fatigue) was also positively related to the LDH-total activity. Thortensen and Karlsson (1976) and Tesch (1980) found similar relationships between peak torque and decline in peak torque (absolute and relative) with FT percentage. These relationships appear to support the suggestion that the individuals who can produce the highest forces tend not to be able to maintain those levels over time to the same degree as those who produce more moderate levels. A possible explanation could be that those who produce the highest forces spend more time in the contractile state. Since muscle blood flow is reduced during contractile activity exceeding 30% MVC (Astrand and Rodahl, 1977), the inability to maintain high force levels may be related to reduced blood flow. As no measure of muscle blood flow was made, it was not possible to verify this.

It seems reasonable to suggest that the responses may also be related to the fibre composition. However, since no muscle biopsy sampling was done, this cannot be directly confirmed in the current study.

The relationship between M-Index, which represents the ability to maintain a given percentage of initial force, and TDO, which represents the ability to maintain force for a given amount of time, suggests that individuals who can resist fatigue for a longer period of time also demonstrate the ability to produce a greater amount of relative force once fatigue has occurred. This pattern ("low fatigue" - Figure 12) is consistent with much of the literature that examines the fatigue response of ST fibres. The literature is outlined in Chapter 2; Table 1 and on pages 36 to 38. The second pattern ("high fatigue" - Figure 12) suggested by the correlations describe a short period of time before fatigue and a greater degree of drop-off once fatigue has occurred. This is consistent with the literature examining the fatigue response of FT fibres, as outlined on page 38.

The first type of pattern might also be related to the pacing problem mentioned previously, since a lack of all-out effort might result in a lesser degree of recruitment of the high force-producing FT muscle fibres. Examples of these two suggested patterns may be found in Figure 13, page 86. The lack of correlation seen for the women between TDO and M-Index again emphasizes the differences in the force production fatigue response.

The very high correlation (r=0.99) between lactate samples taken at two and three minutes post exercise may indicate that;

a) one minute may not be enough time to see a significant change in blood lactate concentration,

b) the peak values are reached quickly in this group,

c) the values plateau around 2 and 3 minutes.

These are consistent with the mean values for men and women from the descriptive results (Table 5, page 69). However, the fact that the 3 minute post exercise sample was the lower value for 15 of the 17 athletes tested suggests that the peak for blood lactate may occur sooner for these subjects than for those in many previous studies. Further study would be necessary to substantiate this, since more extensive lactate sampling would be required to confirm a consistent pattern. That endurance trained athletes may attain peak post-exercise lactate values sooner than others is supported by work of Medbo and Sejersted (1985), which showed marathon runners attaining peak post-exercise blood lactates approximately three minutes earlier than sprint runners.

An interesting result of this study was the high and statistically significant relationship between the maximal VO2rel values and both two and three minute lactate values for the men ($r = 0.79$; $p < 0.05$, and $r = 0.81$; $p > 0.05$ respectively). This indicates that individuals with higher aerobic power may produce less lactate and/or metabolize lactate more efficiently. This is consistent with the literature presented in chapter 2, Table 2. However, this author has found very few studies which have specifically examined the relationship between aerobic power and lactate production during a short term intense effort. McCartney et.al., (1983) found a negative correlation between maximum VO2 (ml/kg/min) and a fatigue index (which represented relative amount of drop-off); this was not seen in the present study. However, they found no association between the maximum VO2 values and post-exercise lactate

values. Goslin and Graham (1985), also found results in agreement with those of the present study, in which a negative correlation ($r=-0.65$, $p < 0.05$) between absolute VO2 values and peak post-exercise lactate samples was found. No explanation was offered for this relationship, and when the relative VO2 values were used in the comparison with peak lactate, only a non-significant coefficient of 0.44 was found. Also, the results for men and women were pooled in Goslin and Graham's study, and this may have obscured any possible gender dependent relationship. A potential indirect factor influencing the relationship between the VO2 and lactate values of the current study could be the positive association between the percentage of ST fibre and maximal VO2 found by Costill et.al., (1976). Since the ST fibres produce less lactate, it is theoretically possible that athletes with very high aerobic capacity levels would have a high percentage of ST fibres and thus a lower lactate producing (and higher lactate metabolizing) capacity.

It has been stated (Vandewalle et.al., 1987) that the longer the duration of the exercise, the more aerobic it is. It is possible that the subject group may be using a higher degree of aerobic metabolism than predicted for this type of exercise, and thus the fatigue response would not be as extreme. Medbo and Sejersted (1985) found that during an exhaustive one minute treadmill run, oxygen uptake accounted for 50% of the energy requirements for marathon runners, compared to 44% for untrained subjects. Similarly, Thomson and Garvie (1981), found that endurance trained subjects contributed 36% of the energy via the aerobic system for an all-out one minute treadmill exercise compared to 27.7% for untrained control subjects. This indicates that aerobic metabolism

may play a greater role than previously thought during intense exercise, particularly for endurance trained athletes.

Also, the exercise may not have been sufficiently intense to stimulate a high glycolytic rate. Katch and Weltman (1979), recommended that the subjects not be told the length of time of the exercise, since they then might pace themselves and not produce all-out effort throughout the duration of the exercise. While the subjects in the current study were aware of the length of the exercise, they were also aware that the ability to produce high peak values and to maintain these high levels (i.e. all-out effort) was at least as important as the ability to maintain throughout the entire two minutes.

The fact that both the F-Peak and F-Mean force variables were linked with the TDO variable for the females suggests that a high force production capability is associated with an ability to maintain a relatively high level of force output for a longer period of time. This result is surprising in light of strong evidence which suggests that a high force production capability is generally associated with a greater fatigue response. These results are in agreement with Clarkson et.al., (1984), whose correlational analyses indicated that the oarswomen who were the strongest showed the least fatigue. It is possible however, that this "high" force output (since it is high only in relation to the other female skiers in the current study) may be produced largely by the ST fibres which characteristically resist fatigue and produce less lactate than do FT fibres.

This response in women is contrary to the men's response and also to the traditional responses as discussed on pages 91 and 92. There is the possibility of a unique fatigue response as a function of the particular characteristics of this group. That the men do not show this positive association between the time to fatigue and the peak force values suggests that the high aerobic capacity is not likely a factor. The possibility exists, however, that these women (or some of them) handle lactate in a manner suggestive of the characteristics of intermediate, or IM, fibres. Schantz (1986) presented evidence of a transformation of fibres from the FT (type IIA) to the IM classification based on examination of changes in ATP-ase staining, isoforms of contractile and regulatory proteins, and metabolic and fibre area characteristics. Of note is the fact that the reported transformation occurred as a result of training in cross country skiing, albeit a form of training that is more consistent with submaximal endurance training than that practiced by the National team members during the season. It is not dissimilar, however, from that practiced by these athletes during their aerobic base training period.

The type of training suggested by Schantz to stimulate the development of IM fibres was practiced by the subjects in his study for a period of 8 weeks. The fact that most of the athletes in the current study had been training to some degree in a similar fashion for a number of years may well enhance the proposed effect. The properties of these IM fibres, as their name suggests, are intermediate between the FT and ST fibres. They exhibit almost as high oxidative capacity, capillary supply and fatigue resistance as the ST fibres, while exhibiting higher glyco-

lytic capacity. There is a possibility, then, that these fibres are fatigue resistant, and yet produce more lactate as a result of enhanced glycolytic activity. It should be noted that this hypothesis is purely speculative, since no muscle fibre sampling was done in the present study. The question of why this response is seen only in women cannot be explained by this hypothesis, particularly since the study by Schantz did not analyze the results separately for males and females.

The F-Peak and F-Mean variables were positively correlated with the La-p2 variable for the women. These relationships are consistent with a more traditional relationship whereby a high rate of glycolytic energy production would be expected to result in high force and high blood lactate. However, the traditional negative relationship between peak lactate and time to fatigue was not supported in the current study since these variables (La-p2 and TDO) showed a positive correlation. While the coefficient value was moderate, and demonstrated only borderline significance ($p < 0.06$), the results are particularly noteworthy since one might logically expect that a correlation between peak lactates and maintenance of force should be negative. As well, the significant positive correlations of TDO with the F-Peak and F-Mean values do not support a traditional pattern of response in that one would not expect the stronger athletes to go the longest.

A high degree of correlation and significance was found between the La-p2 value and both peak and mean force values. These relationships might be expected, since force production during an intense exercise would be expected to require a high rate of glycolysis and thus lactate production.

When using a correlational matrix to analyze results, it must be borne in mind that correlations do not prove cause and effect. The small sample sizes must also be considered in the interpretation, particularly where the significance is not as strong. While several relationships were strong and a number of potential patterns emerged, not all the relationships were highly significant. When this is considered in combination with the sample size, it is obvious that care must be taken in the interpretation of these results, and that further study is necessary to verify the relationships and patterns found in this study.

In summary, the results of this study indicate that there are distinct differences in the fatigue response between elite female and male cross country skiers. While the relationships between peak force and mean force, and between post 2 minute and post 3 minute lactate values are similar for both genders, the patterns diverge considerably with regard to the other variables. The two fatigue patterns found for men are each consistent with the force fatigue properties of the two major fibre types. The relationship between VO2rel and lactate is also consistent with the properties of the ST muscle fibres. Further study involving muscle biopsy analysis would be required to confirm this potential mechanism to explain these results.

The women, on the other hand, show unique responses with regard to both muscular fatigue patterns and to the relationship between force and blood lactate. That the response of the stronger women would be of advantage in cross country ski racing seems likely, and may potentially provide an area for further study and development.

The differences in the responses between males and females and in particular the unique response of the women, indicates that generalizations regarding the traditional relationships between the variables studied must be considered carefully. These must be considered in terms of both gender and the physical and fitness characteristics of the subjects.

V

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The purpose of this study was to investigate the force and blood lactate generated by elite male and female cross country skiers during two minutes of intense rollerboard exercise. The relationships between blood lactate, which has been found to be highly associated with fatigue, and force production, which can provide indications of fatigue, are of interest in understanding the limitations to this type of performance. The characteristics of the subjects, both male and female, may restrict the findings to highly aerobically fit individuals, but they also provide a unique opportunity to learn more about fatigue among a group representing the high end of the spectrum of aerobic fitness. The conclusions of this study are:

1. There are significant differences between the male and female skiers for the following variables;

    a) F-Peak

    b) VO2rel

    c) Weight

2. There is a strong positive relationship between peak force output and mean force output in both male and female cross country skiers in an

intense two minute rollerboard exercise.

3. Significant differences in the correlations for the dependent variables were observed between males and females;

    a) TDO (resistance to fatigue in time) and M-Index (degree of force maintenance)

    b) F-Peak (absolute peak force) and M-Index

    c) DO-Index (relative degree of fatigue) and M-Index

    d) TDO and La-p2 (post exercise lactate value)

4. The women in this study show unique relationships between strength and fatigue, and between fatigue and blood lactate.

5. Different fatigue patterns were found both among and between male and female cross country skiers.

6. Only the men, who had significantly higher maximal VO2 values, showed any relationship between this variable and the dependent variables. However, the only significant (negative) correlation was with the La-p2 and La-p3 variables.

5.2 RECOMMENDATIONS

1. Because of the strong relationship between maximal VO2 and post exercise blood lactate shown by the men in this study, it is recommended that such traditional fitness indicators be included in further studies of force and lactate responses. This is particularly important with subjects for whom aerobic fitness is a significant performance factor.

2. In subsequent work, it is recommended that fibre type distribution be analyzed using a muscle or muscle group which is heavily recruited during the sport or training specific exercise.

3. Further investigation of post-exercise blood lactate (ie longer period of time for post-exercise collection) be made in order to examine the removal pattern of lactate from the blood.

4. Confirmation of gender differences in response to short term intense exercise should be made using larger sample sizes.

BIBLIOGRAPHY

Andrews,J.G., Biomechanical measures of muscular effort. Med. Sci. Sp. 15(3) pp.199-207 1983

Asmussen,E., Muscle fatigue. Med. Sci. Sp. 11(4) pp.313-321 1979

Asmussen,E., Hansen, O., Lammert,O., The relationship between isometric and dynamic strength in man. Communications from the Testing and Observations Institute of the Danish National Association for Infantile Paralysis No. 2 1965

Asmussen,E., Klausen,E., Lactate production and anaerobic work capacity after prolonged exercise. Acta Physiol. Scand. 90(1) pp.731-742 1974

Astrand, P.O., Aerobic and anaerobic sources in exercise. Medicine and Sport pp. 22-37 1981

Astrand, P.O., Principles in ergometry and their applications in sports practice. Int. J. Sp. Med. 5 pp.102-105 1984

Astrand,P.O., Hultman,E., Juhlin-Dannfelt,A., Reynolds,G., Disposal of lactate during and after strenuous exercise in humans. J. Appl. Physiol. 61(1) pp. 338-343 1986

Astrand, P., Rodahl, K., Textbook of Work Physiology McGraw-Hill Book Company, New York 1977

Barnes,W.S., The relationship between maximum isokinetic strength and isokinetic endurance. Research Quarterly 51(4) pp. 714-717 1981

Bar-Or,O., The Wingate Test: An update on methodology, reliability and validity. Sp. Med. 4 pp. 381-394 1987

Bar-Or,O., Dotan,R., Inbar,O., Rothstein,A., Karlsson,J., Tesch,P., Anaerobic capacity and muscle fibre type distribution in man. Int. J. Sp. Med. 1(2) pp.82-85 1980

Belcastro,A., Rossiter,M., Low,M., Sopper, M., Calcium activation of sarcoplasmic reticulum ATP-ase following strenuous activity. Can. J. Physiol. Pharm. 59 pp.1214-1218 1981

Bergh,U., Physiology of cross country ski racing M. Brady and M Hadler(trans.) Human Kinetics Publishers Inc, Illinois, pp.18-37 1980

Bergh,U., Kanstrup,I., Ekblom,B., Maximal oxygen uptake during exercise with various combinations of arm and leg work. J. Appl. Physiol. 41(2) pp.191-196 1976

Bianchi, C.P., Muscle fatigue and the role of transverse tubules. Science 215 pp.295-296 1982

Bigland-Ritchie,B., Johansson,R., Woods,J., Does a reduction in motor drive necessarily result in force loss during fatigue? Inter. Symp. Biochem. Ex. pp.864-870 1983

Bigland-Ritchie,B., Jones,D.A., Hosking, G.P.,Edwards,R.H., Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. Clin. Sc. Mol. Med. 54 pp.609-614 1978

Bohannon,R.W., Contribution of neural and muscular factors to short duration tension developing capacity of skeletal muscle. J. Orth. Sp. Phys. Ther. 5(3) pp.139-147 1983

Bouchard,C., Taylor, A., Dulac,S., Testing anaerobic capacities and powers in athletes. In MacDougall,J., Wenger,H., Green, H., (eds.) Physiological Testing Of Elite Athletes. Can. Assoc. Sp. Sci. pp.61-73 1982

Boulay,M.R., Lortie, G., Simoneau, J., Hamel,P., Leblanc,C., Bouchard,C., Specificity of aerobic and anaerobic work capacities and powers. Int. J. Sports Med. 6 pp.325-328 1985

Brostrom,C., Hunkeler,F., Krebs,E., The regulation of skeletal muscle phosphorylase kinase by Ca++. J. Biol. Chem. 247(7) pp.1961-1967 1971

Burke,R.E., Edgerton,V.R., Motor unit properties and selective involvement in movement. Exer. Sp. Sci. 3 pp.31-83 1975

Caizzo,V.J.,Perrine,J.,Edgerton,V. R., Training individual alterations of the in-vivo force-velocity relationship. J. Appl. Phys. 51(3) 750-754 1981

Caldwell,J., The Cross Country Skiing Book (6th ed.) Stephan Greene Press, Vermont 1981

Cerretelli,P., Pendergast,D., Paganelli,W., Rennie,D., Effects of specific muscle training on VO2 on-response on early blood lactate. J. Appl. Physiol. 47(4) pp.761-769 1979

Chasiotis,D., Sahlin,K., Hultman,E., Regulation of glycogenolysis in human muscle at rest and during exercise. J. Appl. Physiol. 53(3) pp.708-715 1982

Cheetham,M., Boobis,L., Brooks, S., Williams,C., Human muscle metabolism during sprint running. J. Appl. Physiol. 61(1) pp.54-59 1986

Christensen,E.H., Hogberg, P., Physiology of skiing Arbeitsphysiologie 14 pp.292-303 1950

Clarkson,P., Graves,J., Melchionda,A., Johnson,J., Isokinetic strength and endurance and muscle fiber type of elite oarswomen. Can. J. Appl. Sp. Sc. 9(3) pp.127-132 1984

Costill,D., Fink,W., Pollock,M., Muscle fibre composition and enzyme activity of elite distance runners. Med. Sci. Sp. Ex. 8 pp. 96-100 1976

Dainty, D.A., The relationship of anaerobic capacity to selected performance tests. Eugene, Oregon Microfilm Publications Thesis, University of Montana 1971

Danforth,W.H., Activation of the glycolytic pathway in muscle. In Chance,B., and Estabrook,R.,(eds) Control of Energy Metabolism Academic Press, New York, 1965

Dawson,J., Gadian,D., Wilkie,D., Muscular fatigue investigated by phosphorous magnetic nuclear resonance. Nature 274 pp.861-866 1978

DeBruyn-Prevost,P., Determination of anaerobic physical fitness. Kinanthropology II.Conference;International Symposium of Kinanthropology. Baltimore pp. 581-588 1978

Denny-Brown,D., The Cerebral Control of Movement Liverpool University Press, Liverpool pp.198-199 1966

diPrampero,P., Peeters,L., Margaria,R., Alactic 02 debt and lactic acid production after exhausting exercise in man. J. Appl. Phys. 34(5) pp.628-632 1973

Donaldson,S., Effect of acidosis on maximum force generation in peeled mammalian skeletal muscle fibres. Inter. Symp. Biochem. Ex. pp.126-133 1983

Donaldson,S., Hermanssen,L., Differential direct effects of H+ on Ca-activated force generating properties from the soleus, cardiac, adductor magnus muscles of rabbits. Pflugers Arch. 376 pp.55-65 1978

Donovan,c., Brooks,C., Endurance training affects lactate clearance, not lactate production. Am. J. Physiol. 244 pp.83-92 1983

Drummond,G., Harwood,J., Powell, C., Studies on the activation of phosphorylase in skeletal muscle by contraction and by epinephrine. J. Biol. Chem. 244(15) pp.4235-4240 1969

Edgerton,V.R., Neuromuscular adaptations to power and endurance work. Can. J. Sp. Sci. 1 pp.49-48 1976

Edgerton,V.R., Roy,R., Gregor,R., Hagell L., Wickiewicz,T., Muscle fibre activation and recruitment. Inter. Symp. Biochem. Ex. pp.31-39 1983

Edwards, R., Human muscle function and fatigue. C.I.B.A Foundation - Human Muscle Fatigue pp. 1-18 1982

Edwards,R., Biochemical bases of fatigue in exercise performance. Inter. Symp. Biochem. Ex. pp.3-28 1983

Ekstrom, P., Force interplay in cross country skiing Scand. J. Sp. Sci. 3(2) pp.69-76 1981

Essen,B., Haggmark,T., Lactate concentration in type I and type II muscle fibres during muscular contraction in man. Acta Physiol. Scand. 95 pp.344-346 1975

Fabiato,A., Fabiato,F., Effects of pH on the myofilaments and sarcoplasmic reticulum from cardiac and skeletal muscle. J. Physiol. 276 pp.233-255 1978

Fitts,R., Holloszy,J., Lactate and contractile force in frog muscle during the development of fatigue and recovery. Am. J Physiol. 231 pp.430-433 1976

Fitts,R., Kim, D., Witzmanne,F., The development of fatigue during high intensity and endurance exercise. Exercise and Health in Disease ch.9 pp.118-135 1978

Forsberg,A., Tesch,P., Karlsson,J., Effects of prolonged exercise on muscle strength performance. Biomechanics VI vol 2A, University Park Press, Maryland pp.62-67 1978

Fujitsuka,N., Yamamoto,T., Ohkuwa,T., Saito,M., Miyamura,M., Peak blood lactate after short periods of maximal treadmill running. Eur. J. Appl. Physiol. 48 pp.289-296 1982

Gollnick,P.D., Energy production and lactic acid formation Physiol. Asp. Sp. Fit. Chicago Athletic Institute pp.16-19 1968

Gollnick,P.D., Fatigue in retrospect and prospect. Inter. Symp. Biochem. Ex. pp.909-921 1983

Gollnick,P.D., Hermanssen,L., Biochemical adaptations to exercise: Anaerobic metabolism. Exer. Sp. Sci. 1 pp.1-43 1974

Gollnick,P., Matoba,H., The muscle fibre composition of skeletal muscle composition as a predictor of athletic success. Am. J. Sp. Med. 12(3) pp.212-216 1984

Gollnick,P., Piehl,K., Saltin,B., Selective glycogen depletion patterns in human muscle fibres after exercise of varying intensity and at varying pedelling rates. J. Physiol. 241 pp.45-57 1974

Goslin,B., Graham,T., A comparison of 'anaerobic' components of 02 debt and the Wingate test Can. J. Appl. Spt. Sci. 10(3) pp.134-140 1985

Green,H., Houston, M., Thompson,T., Sutton,J., Gollnick,P.D., Metabolic consequences of supramaximal arm work performed during submaximal leg work J. Appl. Physiol. 46(2) pp.249-255 1979

Green, H., Houston, M., Thomson, J., Fraser, I., Fibre type distribution and maximal activities of enzymes involved in energy metabolism. Int. J. Sports Med. 5(4) pp.198-201 1984

Grimby,L., Hannerz,J., Firing rate and recruitment order of toe extensor motor units in different modes of voluntary contraction. J. Physiol. 264 pp.865-879 1977

Hakkinen,K., Komi,P., Tesch,P., Effect of combined concentric and eccentric training and detraining on force-time, muscle fibres, and metabolic characteristics of leg extensor muscles. Scand. J. Sp. Sci. 3(2) pp.50-58 1981

Haymes,E., Dickinson,A., Characterisics of elite male and female ski racers. Med. Sci. Sp. Ex. 12(3) pp.153-158 1980

Henneman,E., Olson, C., The relations between structure and function in the design of skeletal muscles. J. Neurophysiol. 28 pp.581-598 1965

Hermanssen,L., Anaerobic energy release. Med. Sci. Sp. Ex. 1(1) pp.32-38 1969

Hermanssen,L., Muscular fatigue during maximal exercise of short duration. Medicine and Sport 13 pp.45-52 1981

Hermanssen,L., Effect of metabolic changes on force generation in skeletal muscle during muscular exercise. C.I.B.A. Foundation - Human Muscle Fatigue pp.75-88 1982

Hermanssen,L., Orheim,A., Sejersted, O.M., Metabolic acidosis and changes in water and electrolyte balance in relation to fatigue during maximal exercise of short duration. Int. J. Sports Med. 5 pp. 110-115 1984

Hickson,E., The Physican and Sports Medicine Guide to Cross Country Skiing McGraw-Hill Publishers, N.Y. pp.38-42 1980

Hultman,E., Sahlin,K., Acid-base balance during exercise Ex. Sp. Sci. Rev. 8 pp.41-128 1980

Hultman,E., Sjoholm,H., Sahlin,K., Edstrom,L., Glycolytic and oxidative energy metabolism and contraction characteristics of intact human muscle. C.I.B.A. Foundation - Human Muscle Fatigue pp.19-40 1982

Huxley,A.F., Reflections on Muscle Princeton University Press, N.J. ch. 5 pp.68-79 1980

Huxley,A.F., Muscle structure and theories of contraction. Prog. Biophys. Chem. 7 pp.255-318 1957

Ivy,J., Withers,R., Van Handel,P., Elger,D., Muscle respiratory capacity and fibre type as determinants of anaerobic threshold. J. Appl. Physiol. 48 pp.523-527 1980

Jacobs,I., Lactate, muscle glycogen and exercise in man. Acta Physiol. Scand. (suppl 465) 1980

Jacobs,I., Blood lactate:implications for training and sports performance. Sp. Med. pp.10-23 1986

Jones,L.A., Role of central and peripheral signals in force sensation during fatigue. Exper. Neur. 81(2) pp.208-212 1983

Kaneko,M., Komi,P., Aura,O., Mechanical efficiency of concentric and eccentric exercise performed with medium to fast contraction rates. Scand. J. Sp. Sci. 6(1) pp.15-20 1984

Kaneko,M., Fuchimoto,T., Toji,T., Suie,K., Training effects of different loads on force-velocity relationships and mechanical power output in human muscle. Scand. J. Sp. Sci. 5(2) pp.81-121 1983

Karlsson,J., Lactate and phosphagen concentrations in working muscle of man. Acta Physiol. Scand.(suppl.) 358 pp.7-72 1971

Karlsson,J., Localized muscular fatigue: role of substrate metabolism and substrate depletion. Ex. Sp. Sci. Rev. 7 pp.1-42 1979

Karlsson,J., Saltin,B., Lactate, ATP and CP in working muscle during exhaustive exercise in man.
J. Appl. Physiol. 29 pp.231-237 1970

Katch,V.L., Kinetics of oxygen uptake and recovery for supramaximal work of short duration. Int Agnew Z. Physiol. 31 pp.197-207 1973

Katch,V.L., Weltman,A., Interrelationship between anaerobic power output, anaerobic capacity, and aerobic power. Ergonomics 22(3) pp.325-332 1979

Kindermann ,W., Simon,G., Keul,J., The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. Eur. J. Appl. Physiol. 42 pp.25-34 1979

Kindermann ,W., Keul, J., Lactate acidosis with different forms of sports activities. Can. J. Appl. Sp. Sci. 2 pp.177-182 1977

Kindermann ,W., Schnabel,A., Schmitt,W., Biro,G., Cassens,J., Weber,F., Catecholamines, growth hormone, cortisol, insulin, and gender hormones in anaerobic and aerobic exercise. Eur. J. Appl. Physiol. 49(3) pp.389-399 1982

Klausen,K., Peihl,K., Saltin, B., Muscle glycogen storage and capacity for anaerobic work. In: Howald, H., Poortmans, J.,(eds) Metabolic adaptations to Prolonged physical Exercise. Birkenhauser, Basel pp.127-129 1975

Knuttgen,H.G., Human performance in high intensity exercise with concentric and eccentric muscle contractions. Int. J. Sports Med. 7 pp.6-9 1986

Komi,P.V., Neuromuscular performance: Factors influencing force and speed production. Scand. J. Sp. Sci. 1 pp.2-15 1979

Komi,P.V., Rusko,H., Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. Scand. J. Reh. Med. Suppl. 3 pp.121-126 1974

Komi,P.V., Biomechanics and neuromuscular performance. Med. Sci. Sp. 16(1) pp.26-28 1984

Komi,P.V., Electronic, mechanical, and metabolic changes during static and dynamic fatigue. Inter. Symp. Biochem. Ex. pp.197-215 1983

Komi,P.V., Mechanical and electrical behaviour of human muscle during maximal concentric and eccentric contractions. Biomechanics IV pp.428-433 1973

Komi,P.V., Physiological and biomechanical correlates of muscle function. Inter. Symp. Biochem. Ex. pp.81-115 1983

Komi, P.V., Rusko H., Vos, J., Vihko, V., Anaerobic performance capacity in athletes. Acta Physiol. Scand. 100 pp.107-114 1977

Kontron Medical Operating Manual for Lactate Analyzer 640 Kontron Medical, Switzerland 1981

Kulig,K., Andrew,G.H., Hay,J.G., Human strength curves. Exer. Sp. Sci. 12 pp.417-466 (157-204) 1984

Lehninger,A., Principles of Biochemistry (3rd ed.) Worth Publishers Inc., N.Y. 1982

MacDougall,J.D., Limitions to anaerobic performance. Conference:Symposium on Science and the Athlete. Ottawa, Coaching Assoc. Can., pp.22-30 1975

MacDougall,J., Wenger,H., Green,H.,(eds.) Physiological Testing of the Elite Athlete. Can. Assoc. Sp. Sc. 1983

Margaria,R., Energy sources for anaerobic work Physiol. Aspects of Sport and Physical Fitness Chigago Athletic Institute pp.20-25, 1968

Margaria,R., Edwards,H., Dill,D., The possible mechanism of contracting and paying the oxygen debt and the role of lactic acid in muscle contraction. Am. J. Physiol. 106 pp.689-695 1933

Mawatari,S., Tagaki,A., Rowland,L., Adenyl cyclase in normal and pathological human muscle. Arch. Neurol. 30 pp.96-102 1974

McCartney,N., Heigenhauser,G., Jones,N., Power output and fatigue of human muscle in maximal cycling. J. Appl. Physiol. 55(1) pp.218-224 1983

McCartney,N., Heigenhauser,G., Jones,N., Effects of pH on maximal power output and fatigue during short-term dynamic exercise. J. Appl. Physiol. 55(1) pp.225-229 1983

McGilvery,R,W., Biochemistry; A Functional Approach (2nd ed) W.B. Saunders Co., Philidalphia pp.463-481 1983

Medbo,J.I., Sejersted,O.M., Acid-base and electrolyte balance after exhaustive exercise in endurance trained and sprint-trained subjects. Acta Physiol. Scand. 125 pp.97-109 1985

Medbo,J., Mohn,A., Tabata,I., Bahr,B., Vaage,O., Sejersted,O., Anaerobic capacity determined by maximal accumulated O2 deficit. J. Appl. Physiol. 64(1) pp.50-60 1988

Merton,P., Voluntary strength and fatigue. J. Physiol. 123 pp.553-564 1954

Meyerhof,O., Kolehydrat und Mitchaure-umsate im Froschmuskel Pflugers Arch 185:11 1920 (as cited in Needham,1977)

Nagata,A., Moritani,T., Muro,M., Critical power as a measure of fatigue threshold and anaerobic threshold. Biomechanics VIII-A+B pp.313-320 1981

Nakamura,Y., Schwartz,A., The influence of hydrogen ion concentration on calcium binding and release by skeletal muscle sarcoplasmic reticulum. J. Gen. Physiol. 59 pp.22-32 1972

Needham, D., Machina Carnis - The Biochemistry of Muscular Contraction in Its Historical Development Cambridge, Cambridge University Press 1971

Newsholme,E.A., Control of carbohydrate utilization in muscle in relation to energy demand and its involvement in fatigue. Medicine and Sport 13 pp.53-62 1981

Niinimaa,V., Dyon,M., Shephard,R., Performance and efficiency of intercollegiate cross country skiers. Med. Sci. Sp. 10(2) pp.91-93 1978

Nosek,T., Kimberly,F., Saltin,B., It is diprotonated phosphate that depresses force in skinned skeletal muscle fibres. Science 236 pp.191-193 1987

O'Bryant,H., Roundtable:Determining factors of strength (Part 1). Nat. Str. Cond Ass. J. 7(1) pp.10-23 1985a

O'Bryant,H., Roundtable:Determining factors of strength (Part 2). Nat. Str. Cond Ass. J. 7(2) pp.10-23 1985b

Ohkuwa,T., Kata,Y., Katsumata,K., Takayuki,N., Miyamura,M., Blood lactate and glycerol after 400-m and 3,000-m runs in sprint and long distance runners. Eur. J. Appl. Physiol. 53 pp.213-218 1984

Pendergast,D., Gerretelli,P., Rennie,P., Aerobic and glycolytic metabolism in arm exercise. J. Appl. Physiol. 47(4) pp.754-776 1979

Perrine,J., Edgerton,V,R., Muscle force-velocity and power-velocity relationships under isokinetic loading. Med. Sci. Sp. 10(3) pp.159-166 1978

Pollack,G.H., The crossbridge theory. Physiol. Rev. 63(3) pp.1049-1107 1983

Poortmans,J., The intracellular environment in peripheral fatigue. Inter. Symp. Biochem. Ex.1983 pp.113-115, 1983

Powers,S., Beadle,R., Magnum,M., Exercise efficiency during arm ergometry. J. Appl. Phys. 56(2) pp.495-499 1984

Ricci,B., Measurement of oxygen debt and of blood lactate and pyruvate. Physical Aspects of Sport and Physical Fitness. Chicago Athletic Institute. pp.12-15, 1968

Robertson, ., Kerrick, ., The effects of pH on submaximal and maximal Ca++ activated tension in skinned frog skeletal muscle fibre. Biophysiol. J. 16 73a 1976

Rube,N., Secher,N., Paradoxical influence of encouragement on muscle fatigue. Eur. J. Appl. Phys. 46(1) pp.1-7 1981

Rusko,H., Havu,M., Karvinen,E., Aerobic performance capacities in athletes. Eur. J. Appl. Physiol. 38 pp.151-159 1978

Rusko,H., Rahkilla,P., Karvinen,E., Anaerobic threshold, skeletal muscle enzymes and fibre composition in young female cross country skiers. Acta Physiol. Scand. 108 pp.263-268 1980

Rusko,H., Physiological adaptations of skating and classical skiing. Coaches Resource Package 6(6) pp.145-146 1988

Saar,P., Scheier,A., Physiological testing of the elite cross country skier. Cross Country Canada, Ottawa pp.18-20 1985

Saar P., The reliability and validity of individual anaerobic threshold in treadmill ski walking. Masters thesis, University of Ottawa, 1985

Sahlin,K., Intracellular pH and energy metabolism in skeletal muscle of man; with special relevance to exercise. Acta Physiol. Scand. (suppl 455) pp.7-45 1978

Sahlin,K., Edstrom,L., Sjoholm,H., Hultman,E., Effects of lactic acid accumulation and ATP decrease on muscle tension and relaxation. Am. J. Physiol. 240 pp.c121-c126 1981

Sahlin,K., The effect of acidosis on energy metabolism and force generation in skeletal muscle. Inter. Symp. Biochem. Ex. pp.151-159 1983

Sale,D., MacDougall,D., Upton, A., McComas, A., Effect of strength training on motoneuron excitability. Med. Sci. Sp. Ex. 15(1) pp.57-62 1983

Saltin,B., The physiologcal and biochemical basis of aerobic and anaerobic capacities in man: effect of training and adaptation. Seminary for coaches in cross country pp.91-175 Valadalen, Sweden 1986

Sapega,A., Drilling,G., The definition and assessment of muscular power. J. Orth. Sp. Phys. Ther. 5(1) pp.7-9 1983

Schantz, P.G., Plasticity of human skeletal muscle. Acta Scand. Physiol. (suppl) 558 pp.1-62 1986

Scheier, A., Cross Country Skiing: Level 2 Technical Manual Cross Country Canada, Ottawa 1983

Schmidtbleicher,D., Strength training-part two; structural analysis of motor strength qualities and its application to training. S.P.O.R.T.S. September 1985

Secher,N., Niels,L., Binkhorst,R., Flemming,B., Maximum oxygen uptake during arm cranking and comdined arm and leg exercise. J. Appl. Physiol. 36(5) pp.515-518 1974

Seliger,V., Dolejs,L., Kasas,V., Dynamometric comparison of maximal eccentric, concentric, and isometric using EMG and energy expendature measurements. Eur. J. Appl. Phys. 45(2/3) pp.235-244 1980

Sharp,N.C., Koutedakis,Y., Anaerobic power and capacity measurements of upper body in elite judo players, gymnasts, and rowers. Aust. J. Sp. Med. 19(3) pp.9-13 1987

Simoneau,J., Lortie,G., Boulay,M., Bouchard,C., Tests of anaerobic alactic and lactic capacity. Can. J. Appl. Sp. Sci. 8(4) pp.266-270 1983

Sjodin,B., LDH and human skeletal muscle. Acta Physiol. Scand. (suppl 436) 1976

Stevens,J., Taylor,A., Fatigue of maintained voluntary muscle contraction in man. J. Physiol. 220 pp.1-18 1972

Tesch,P., Local lactate and exhaustion. Acta Phys. Scand. 104(3) pp.373-375 1978

Tesch,P., Muscle fatigue in man; with special reference to lactate accumulation during short term intense exercise. Acta Physiol. Scand. (suppl. 480) pp.3-48 1980

Tesch,P., Wright,J., Daniels,W., Sjodin,B., Physical performance and muscle metabolic characteristics. Inter. Symp. Biochem. Ex. pp.258-263 1983

Tesch,P., Karlsson,J., Sjodin,B., Muscle fibre type distribution in trained and untrained muscle of athletes. Exercise and Sport Biology Komi, P.,(Ed.) Int'l Series on Sport Sciences Vol 12 pp.79-83 1979

Tesch,P., Wright,J.E., Recovery from short-term intense exercise: Its relation to capillary supply and blood lactate concentration. Eur. J. Appl. Physiol. 52 pp.98-103 1983

Thomson,J., Prediction of anaerobic capacity: A performance test employing an optimal exercise stress. Can. J. Appl. Spt. Sci. 6(1) 21-26 1981

Thomson, J., Garvie, K., A laboratory method for determination of anaerobic energy expenditure during sprinting. Can. J. Appl. Spt. Sci. 6(1) 16-20 1981

Thortenssen,A., Muscle strength, fibre types and enzyme activities in man. Acta Physiol. Scand. (suppl)443 1976

Thortenssen,A., Karlsson,J., Fatiguability and fibre composition of human skeletal muscle. Acta Physiol. Scand. 98 pp.318-322 1976

Vandewalle,H., Peres,G., Monod,H., Standard anaerobic exercise tests. Sp. Med. 4 pp.268-289 1987

Viitasalo,J., Komi, P., Force-Time Characteristics and Fibre Composition in Human Leg Extensor Muscles Eur. J. Appl. Physiol. 40 pp.7-15 1978

Wasserman,K., Beaver,W., Davis,J., Pu,J., Heber,D., Whipp,B.J., Lactate, pyruvate, and lactate-to-pyruvate ratio during exercise and recovery. J. Appl. Physiol. 59(3) pp.935-940 1985

Wenger,H., Reed,A., Metabolic factors associated with muscular fatigue during aerobic and anaerobic work. Can J. Appl. Spt. Sci. 1 pp.43-47 1976

Wilson,J., McCully,K., Mancini,D., Boden,B., Chance,B., Relationship of muscle fatigue to pH and diprotonated Pi in humans; a P-NMR study. J.A.P. 64(6) pp.2333-2339 1988

Woledge,R., Curtin,N., Homsher,G., The crossbridge hypothesis Energetic Aspects of Muscle Contraction ch.1 pp.14-26 1985

Wood,G., Pyke,F.S., LeRossignol,P., Munro,A., Neuromuscular adaptations to training. Biomechanics VIII-A pp.306-311 1981

Wood,J.J., Bigland-Ritchie,B., Linear and nonlinear force relationships in human muscles. Amer.J.Phys.Med. 62(6) pp.287-299 1983

Yokayama,S., Maximum local muscle energy metabolic rate in athletes. J. Anthrop. Soc. Nippon 91(3) pp.363-375 1983

Appendix A

Lactate Values Post Rollerboard Exercise (pilot study, 1985)

	Approximate Times for Lactate Sampling (post-exercise) (minutes:seconds)								
Subjects	2:00	2:20	2:40	3:00	3:20	3:40	4:00	4:20	4:40
CG	6.78	6.93	6.86	7.79	7.56	7.68	---	7.31	7.31
MM	9.64	9.74	9.69	10.10	9.86	9.93	8.50	8.50	8.50
LS	7.52	7.54	7.53	7.60	7.16	7.38	7.48	- - -	7.48
DL	7.36	7.66	7.51	7.78	7.52	7.65	7.52	7.54	7.53
WD	9.92	9.34	9.63	8.98	8.68	8.83	---	---	
PH	- - -	7.40	---	8.56	---	8.56	8.38	8.03	7.68
YB	9.02	9.39	9.88	10.30	10.72	10.51	10.66	10.60	10.63

Note: Subjects and protocol as in thesis

Appendix B

Table 3.1 Correlational Matrix for Pooled Data (body weight included)

Pearson Correlation Coefficients / Probability Statements / N=17

	TDO	FPeak	FMean	DOIndex	M-Index	La-p2	La-p3	VO2rel	Weight
TDO	-								
F-Peak	.129 .622	-							
F-Mean	.450+ .070	.848** .0001	-						
DO-Index	.435+ .081	.714** .001	.347 .172	-					
M-Index	.624** .007	-.252 .330	.075 .774	-.765** .0003	-				
La-p2	.222 .391	.389 .122	.511+ .036	.057 .826	.034 .898	-			
La-p3	.260 .314	.331 .195	.474+ .054	-.069 .793	.029 .912	.965** .0001	-		
VO2rel	.245 .343	.423+ .090	.297 .246	.105 .688	.391 .121	.003 .993	-.092 .726	-	
Weight	.129 .622	.427 .087	.242 .349	.310 .226	-.046 .860	.345 .175	.259 .315	.607 .010**	-

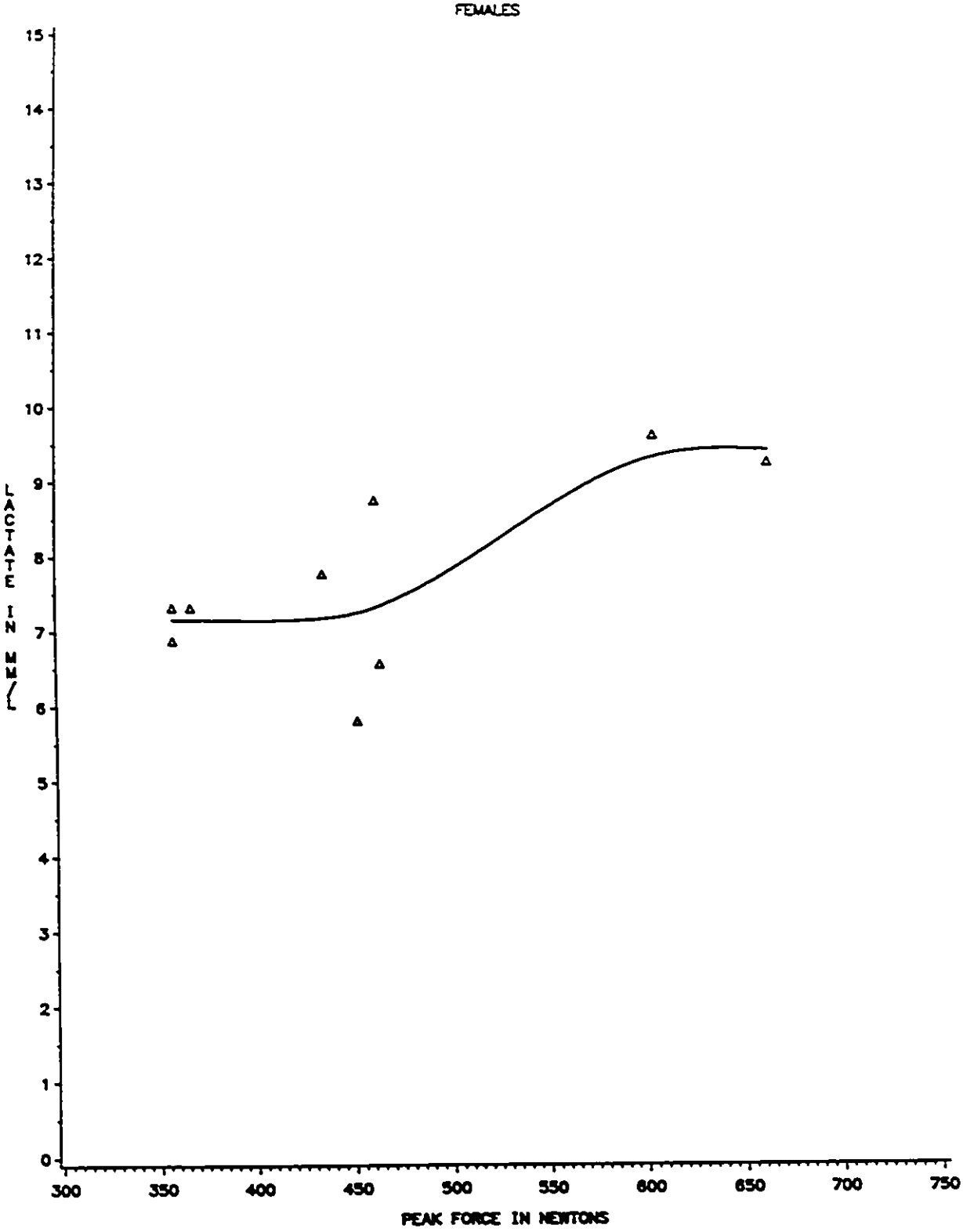
+ Significant at the $p < 0.10$ level

* Significant at the $p < 0.05$ level

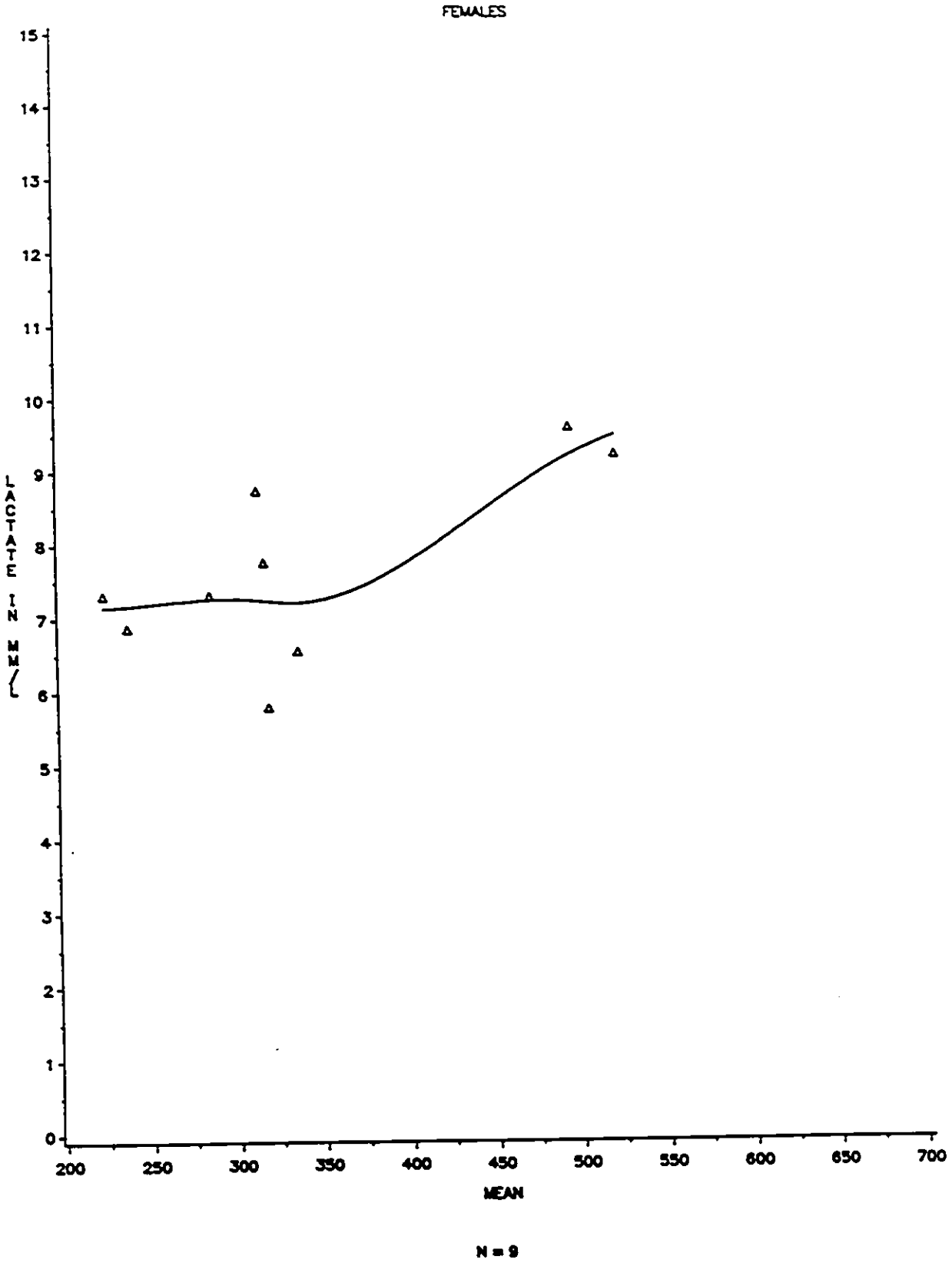
** Significant at the $p < 0.01$ level

See page10 for variable definitions

APPENDIX C: LA–P2 VS F–PEAK

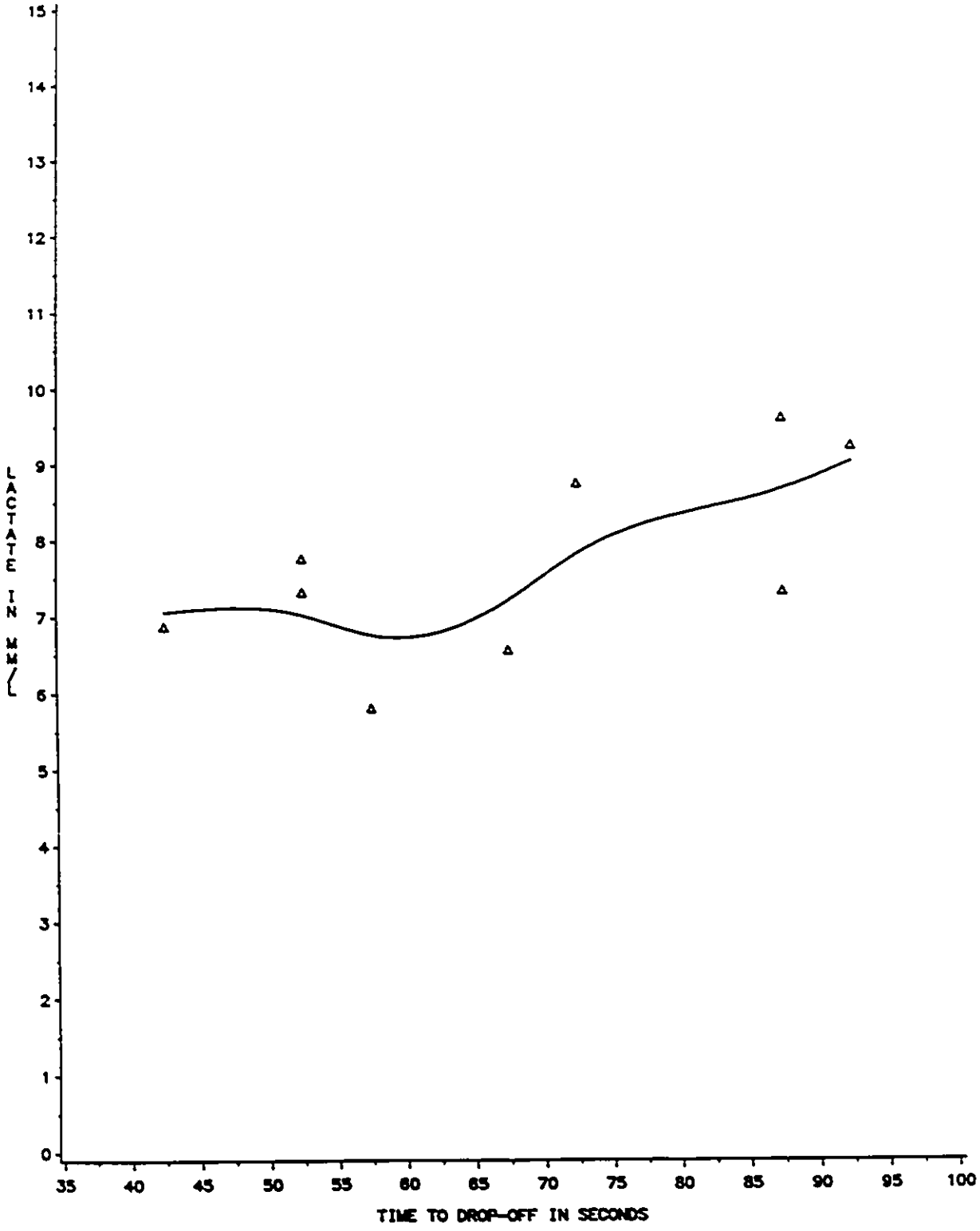


APPENDIX C: LA–P2 VS F–MEAN



APPENDIX C: LA–P2 VS TDO

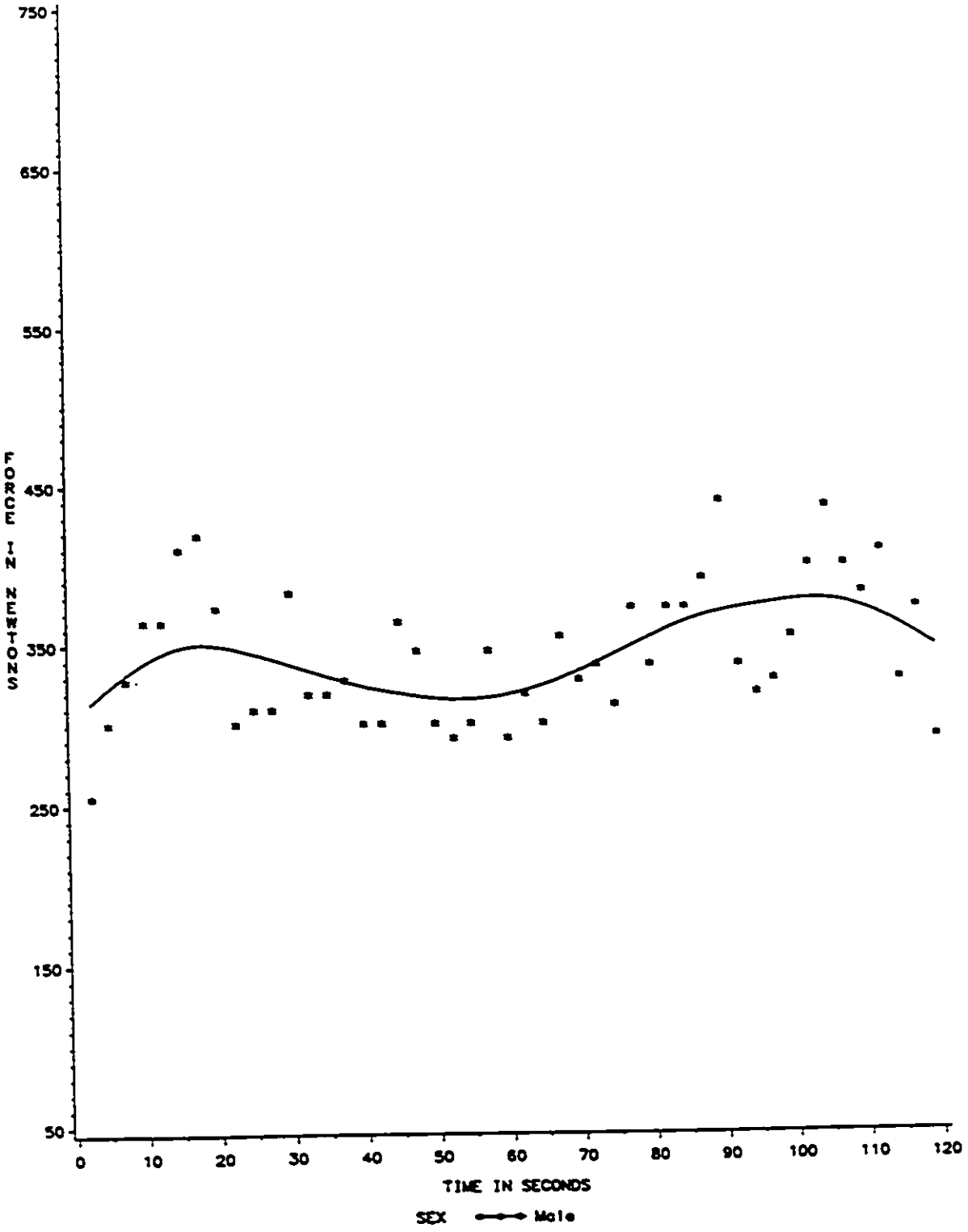
FEMALES

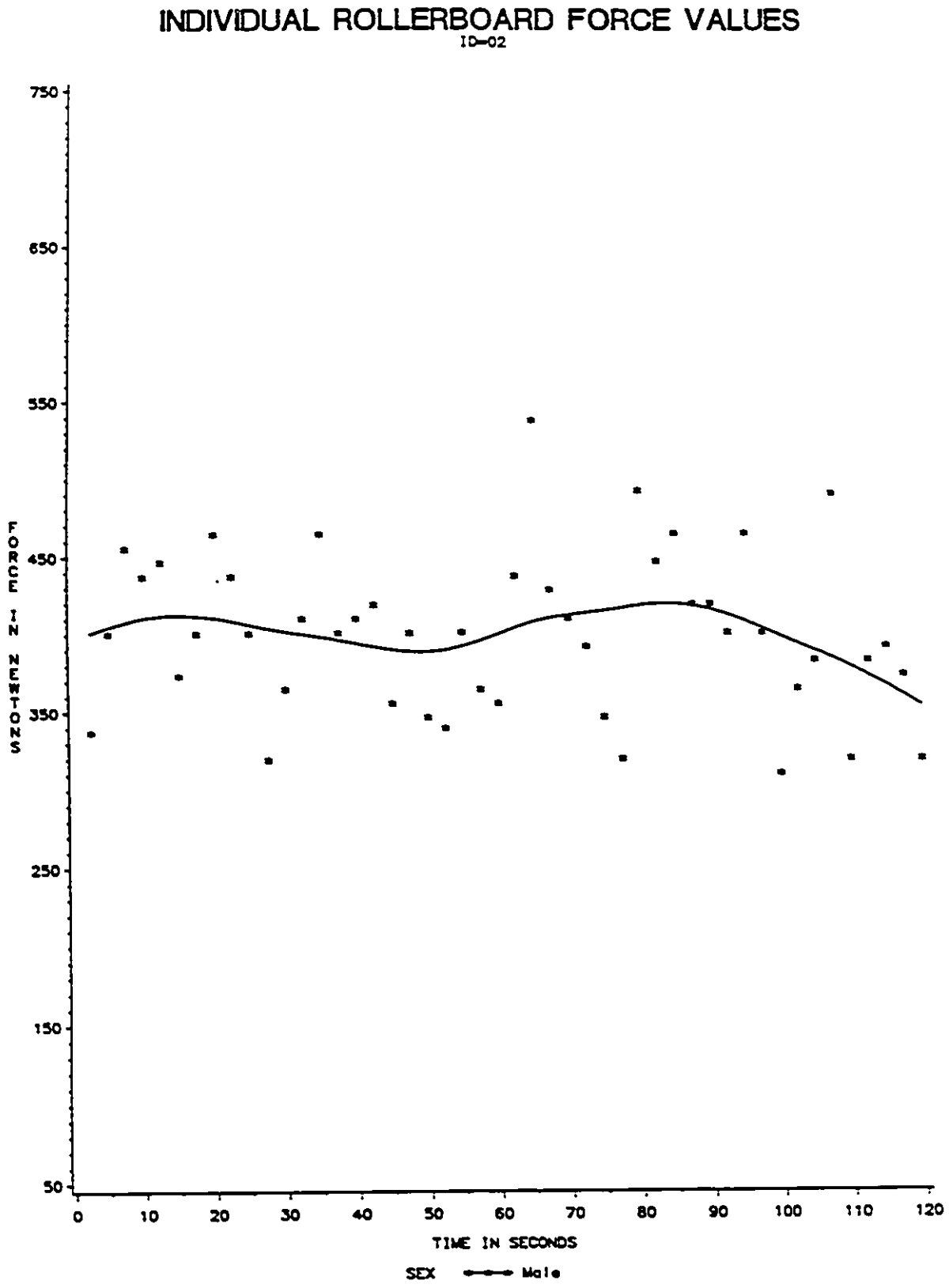


N = 9

INDIVIDUAL ROLLERBOARD FORCE VALUES

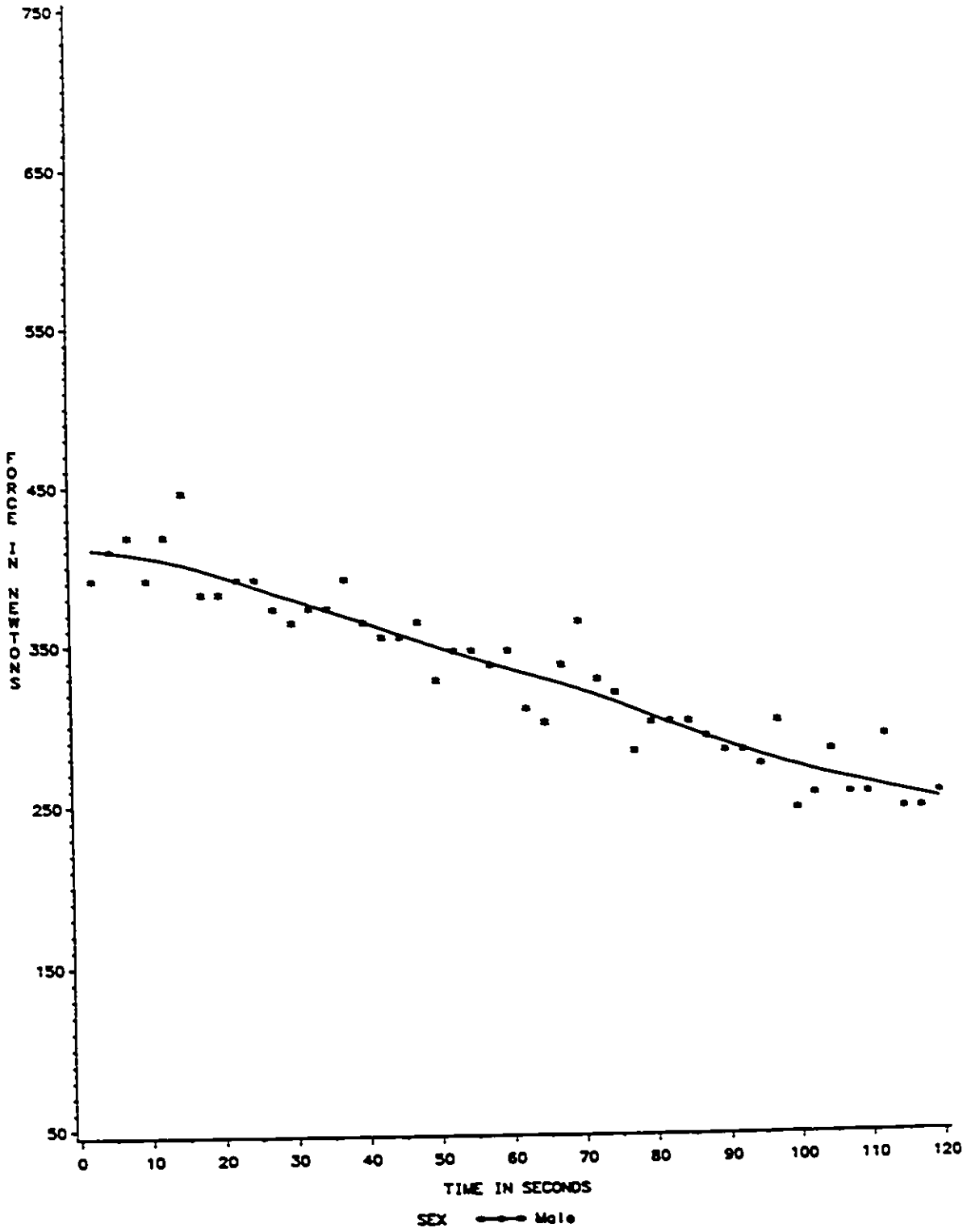
ID=01

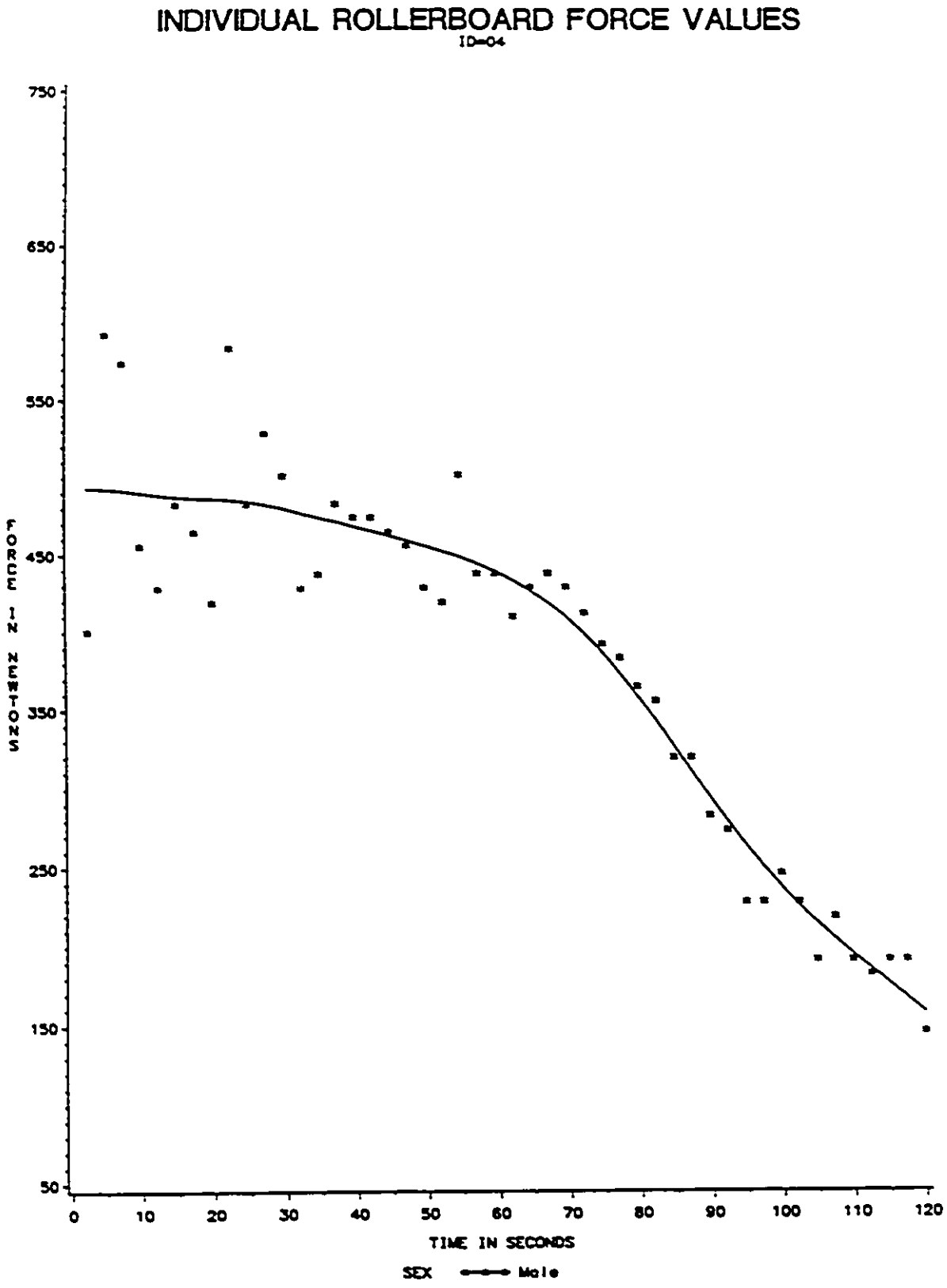



INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=02
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Male

INDIVIDUAL ROLLERBOARD FORCE VALUES

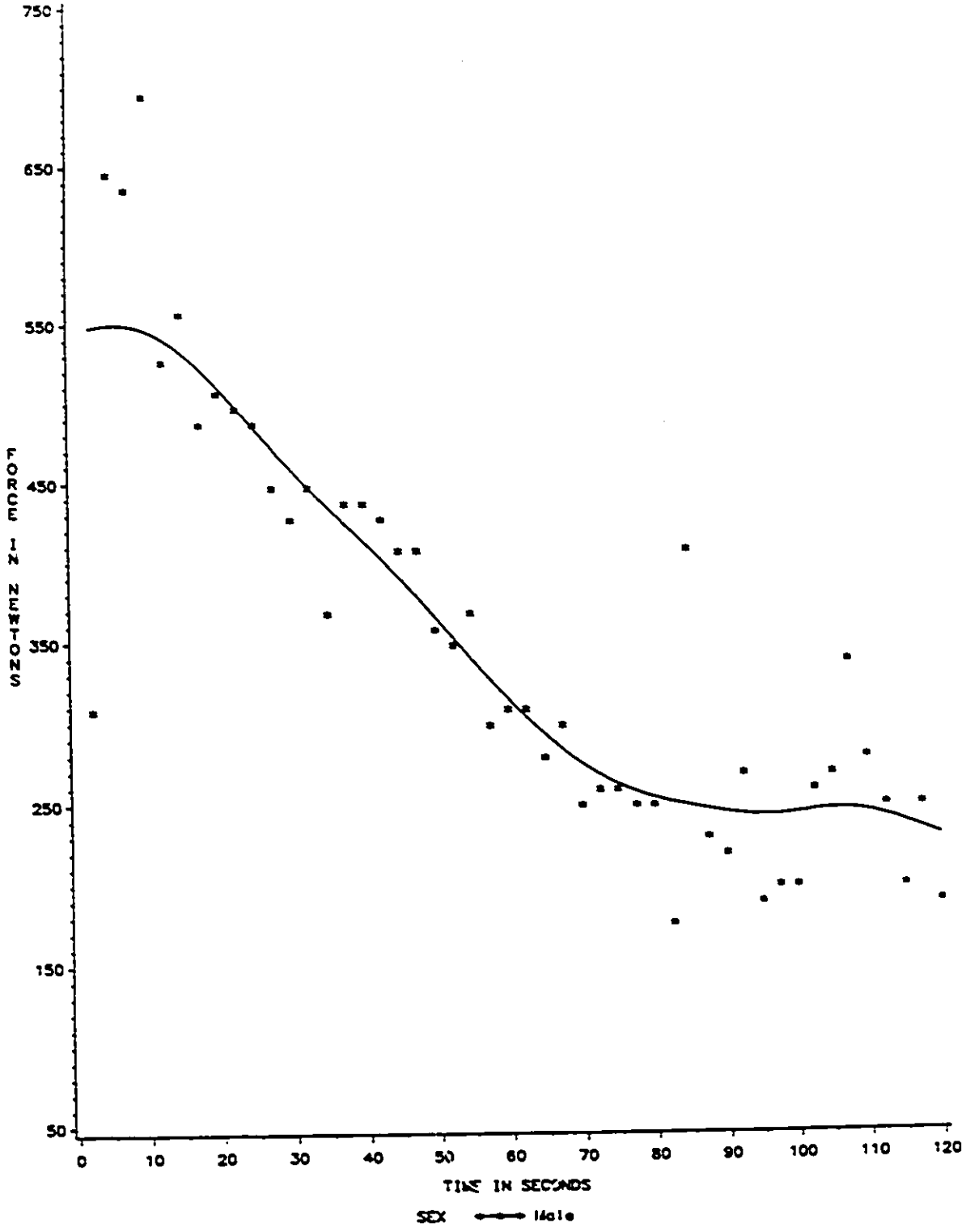
ID=03

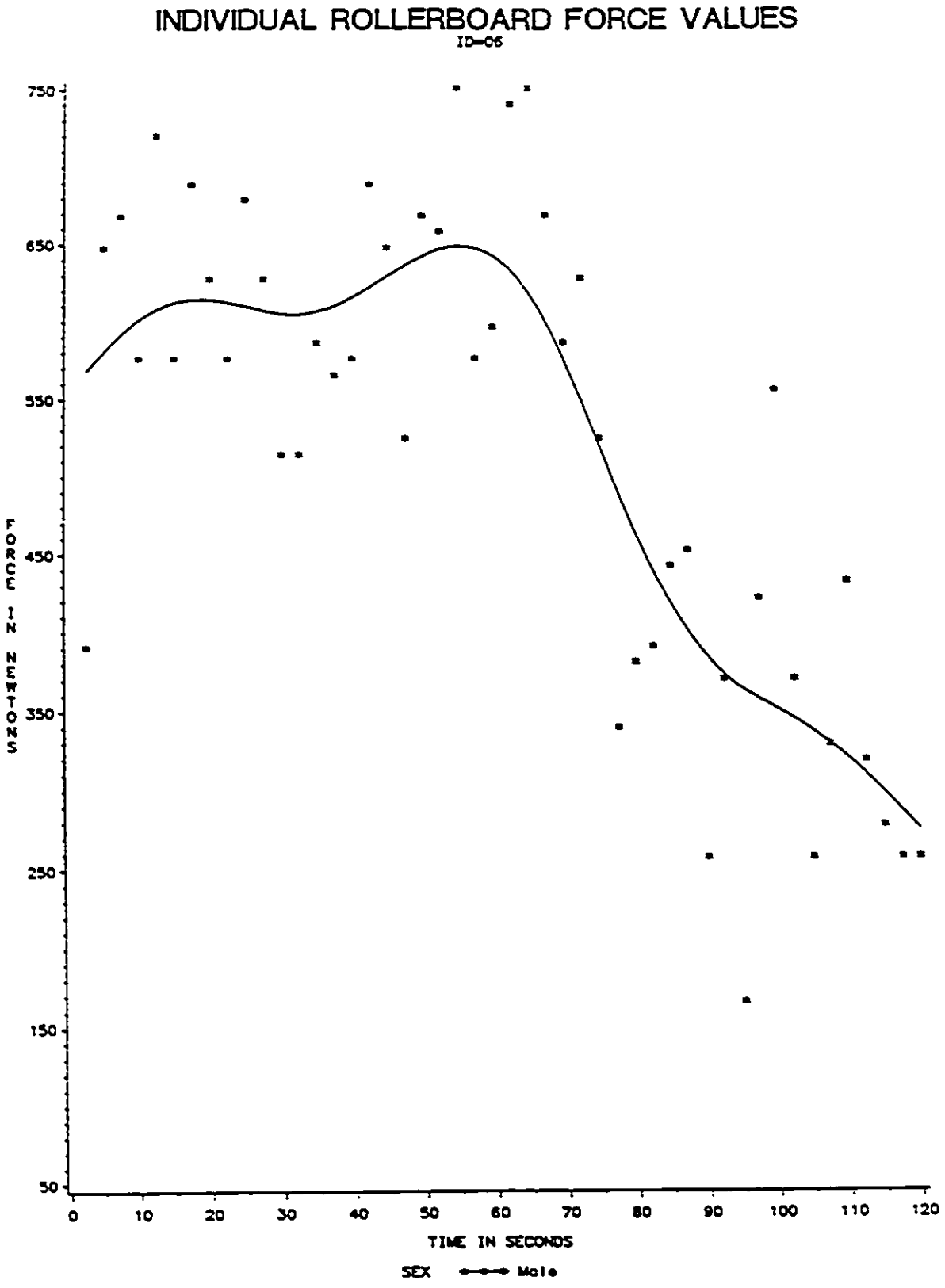



INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=04
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Male

INDIVIDUAL ROLLERBOARD FORCE VALUES

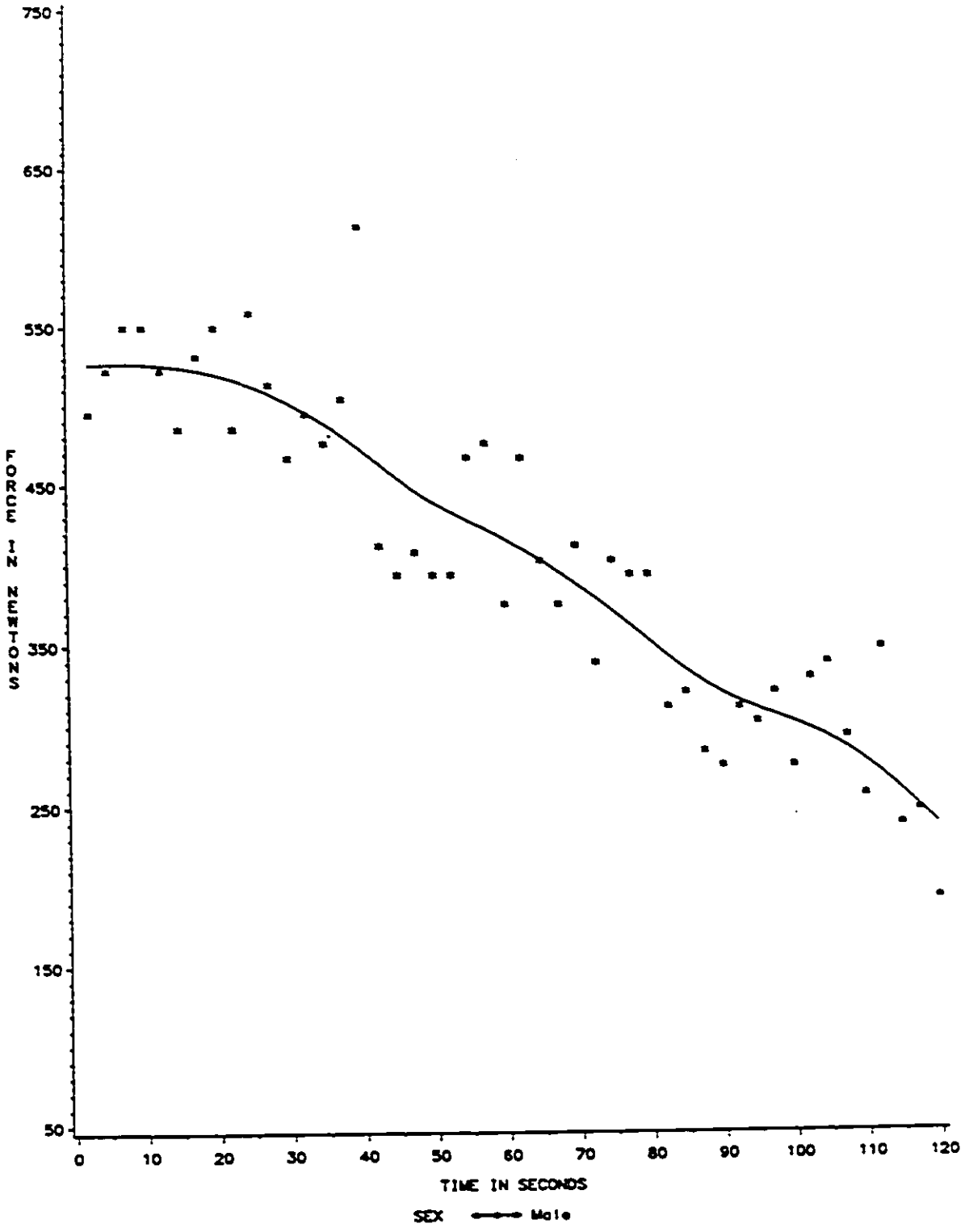
ID=05

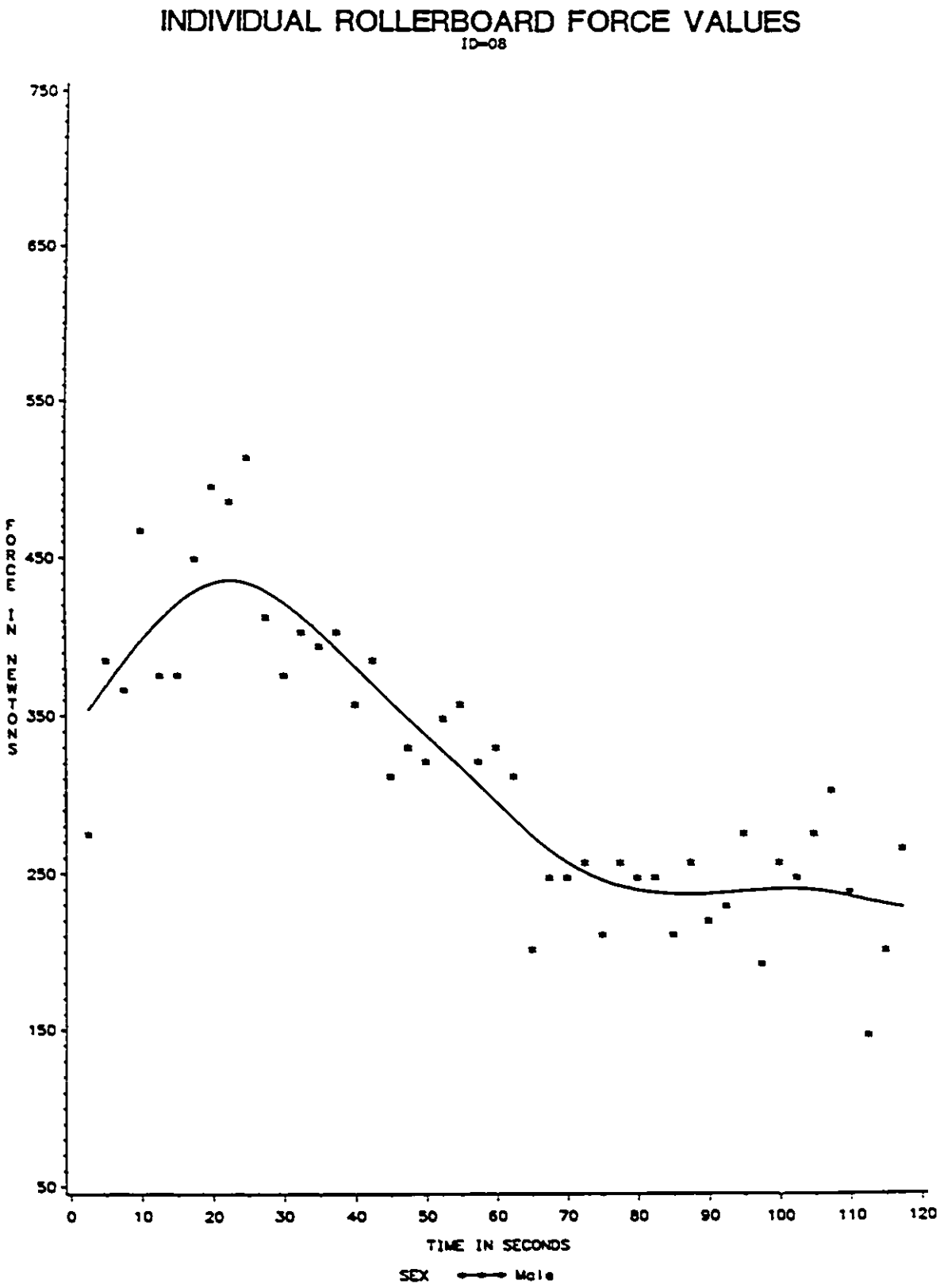



INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=06
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Male

INDIVIDUAL ROLLERBOARD FORCE VALUES

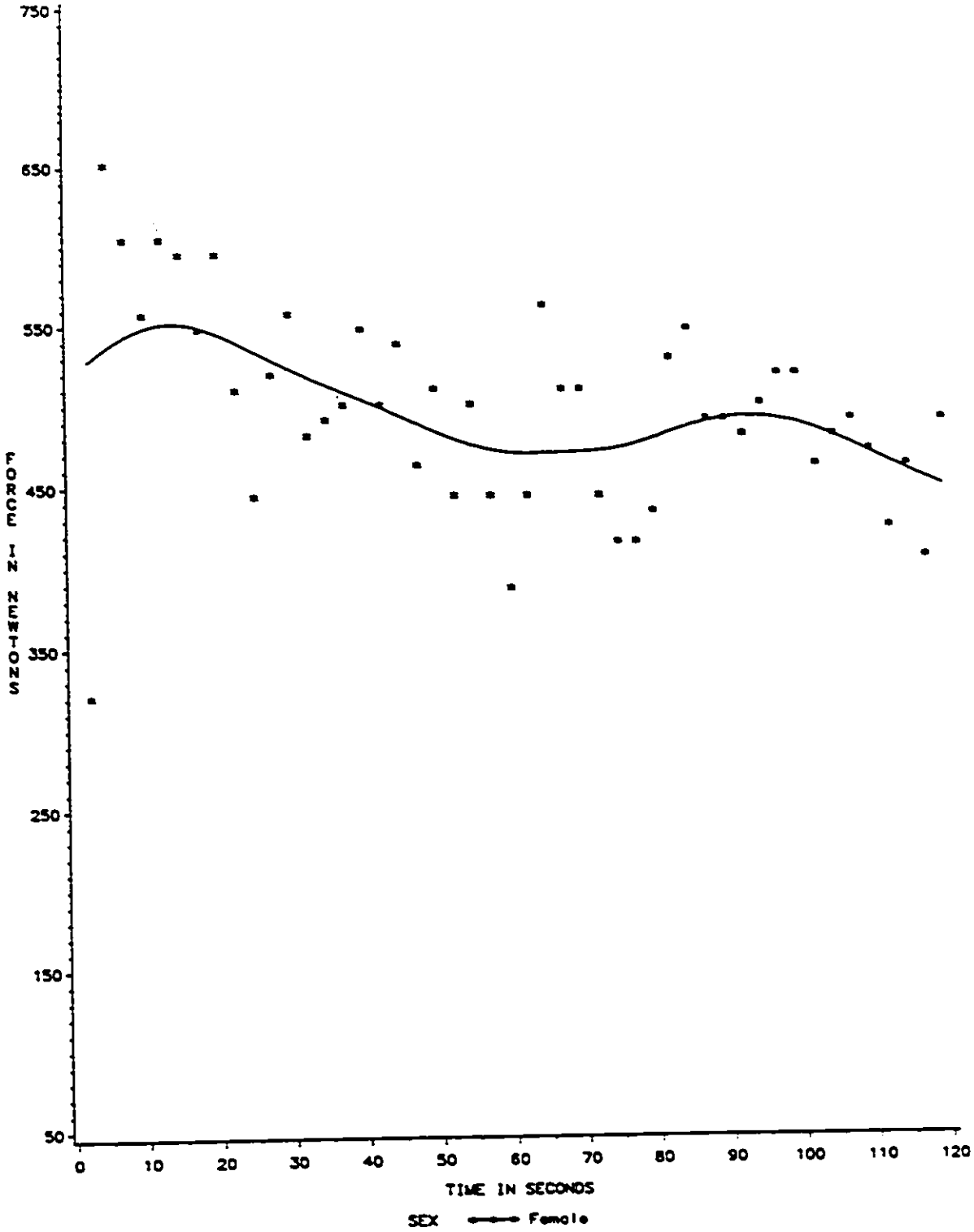
ID=07

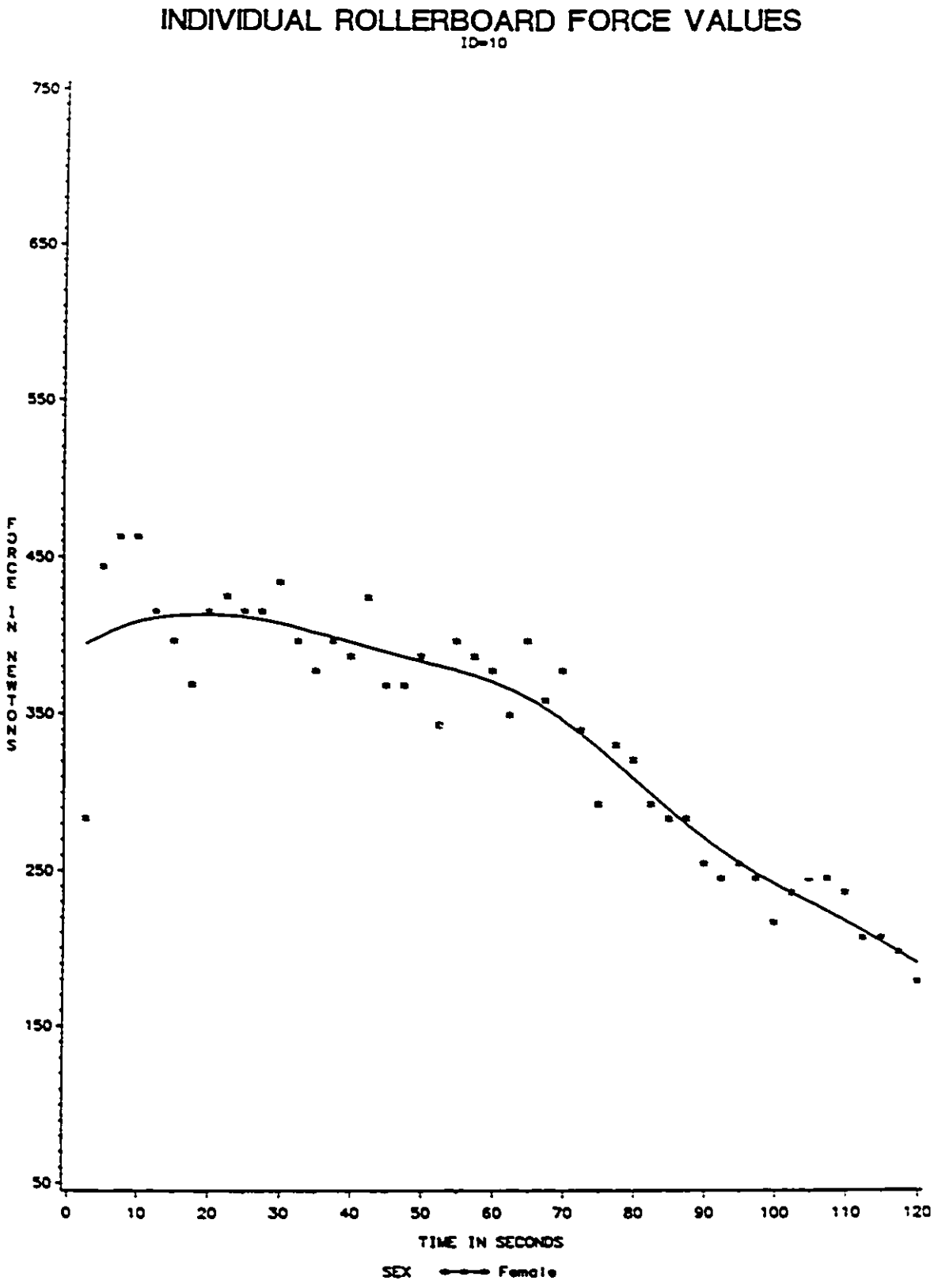


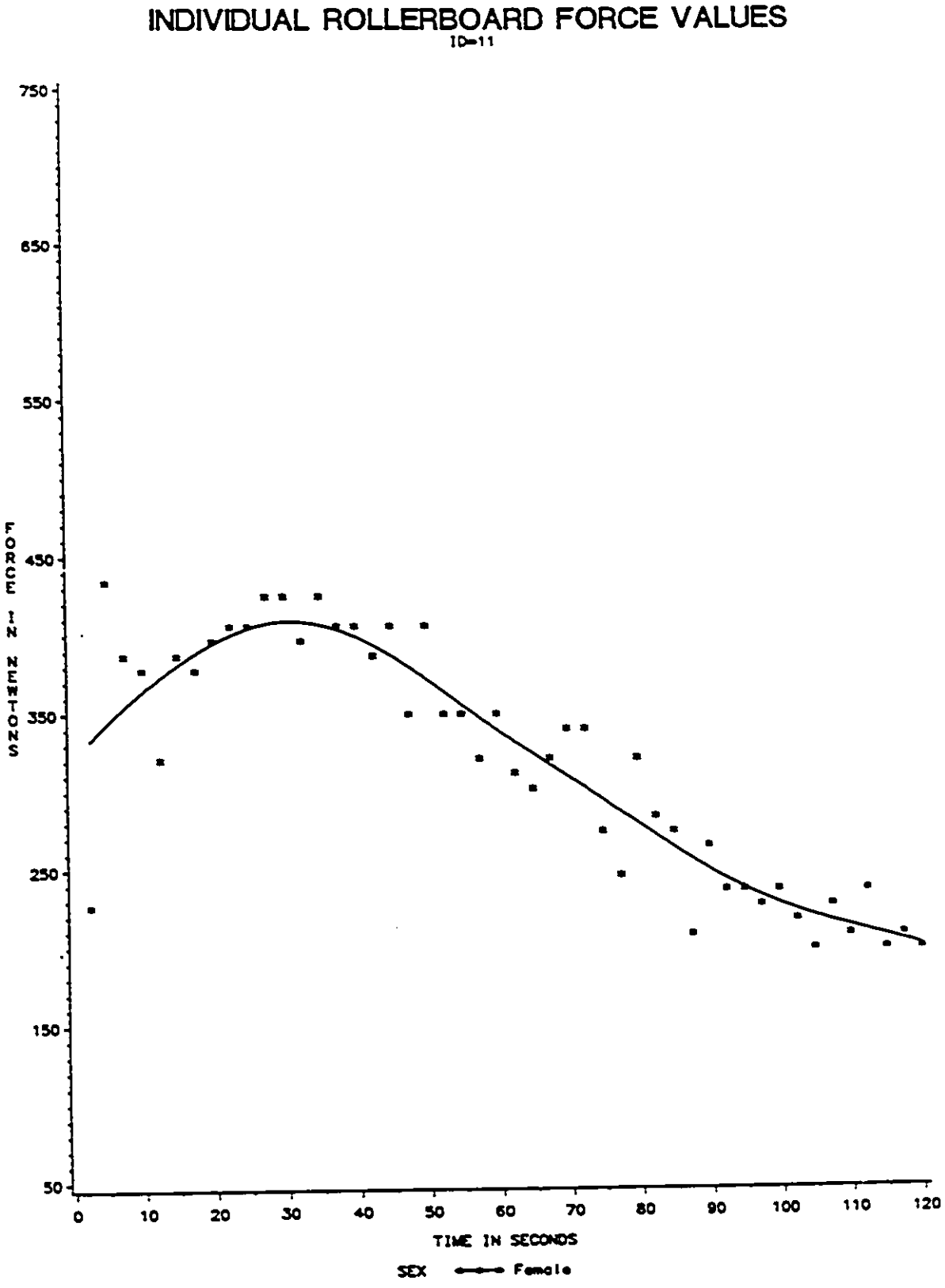

INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=08
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Male

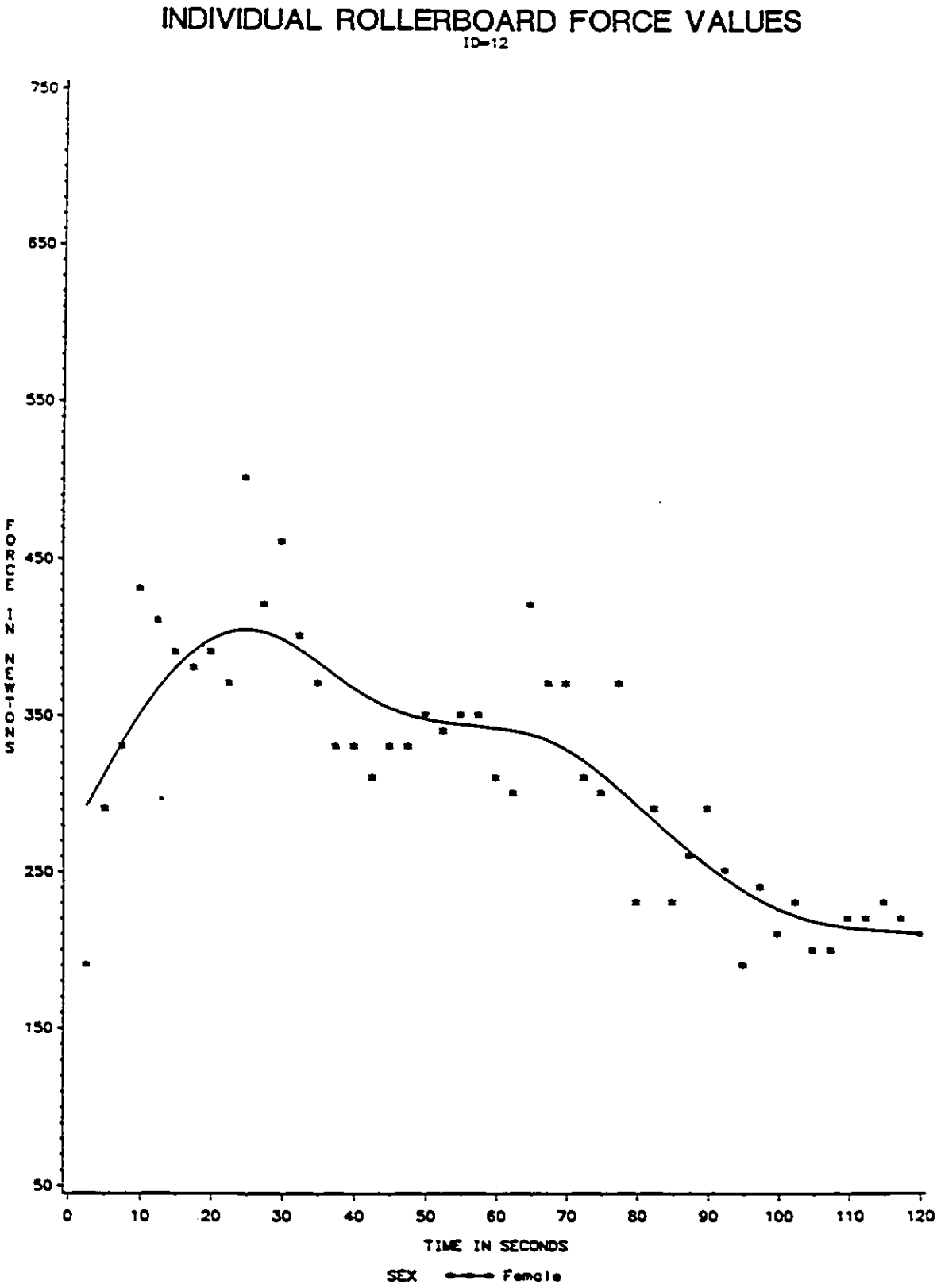
INDIVIDUAL ROLLERBOARD FORCE VALUES

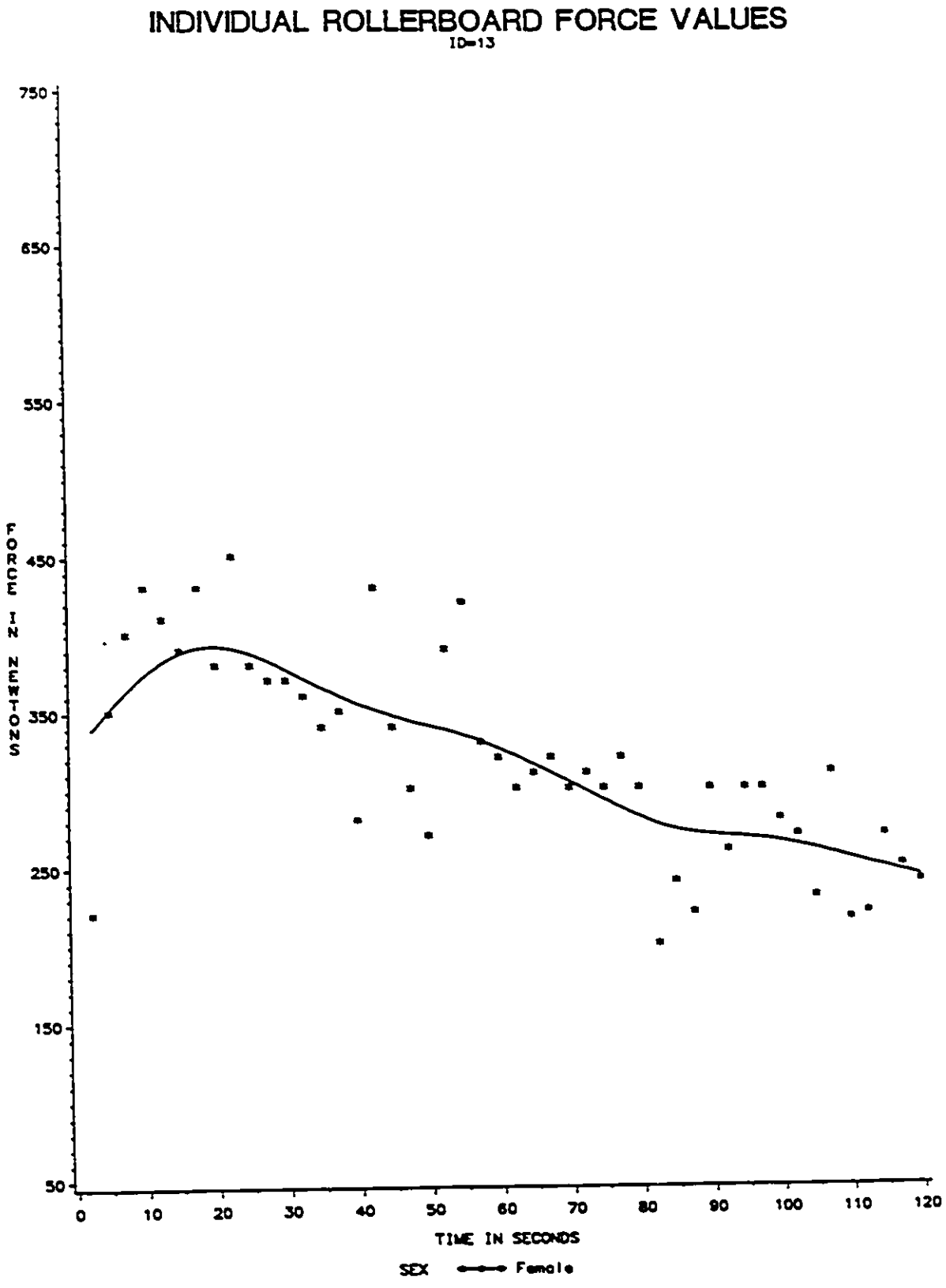
ID=09




INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=10
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Female

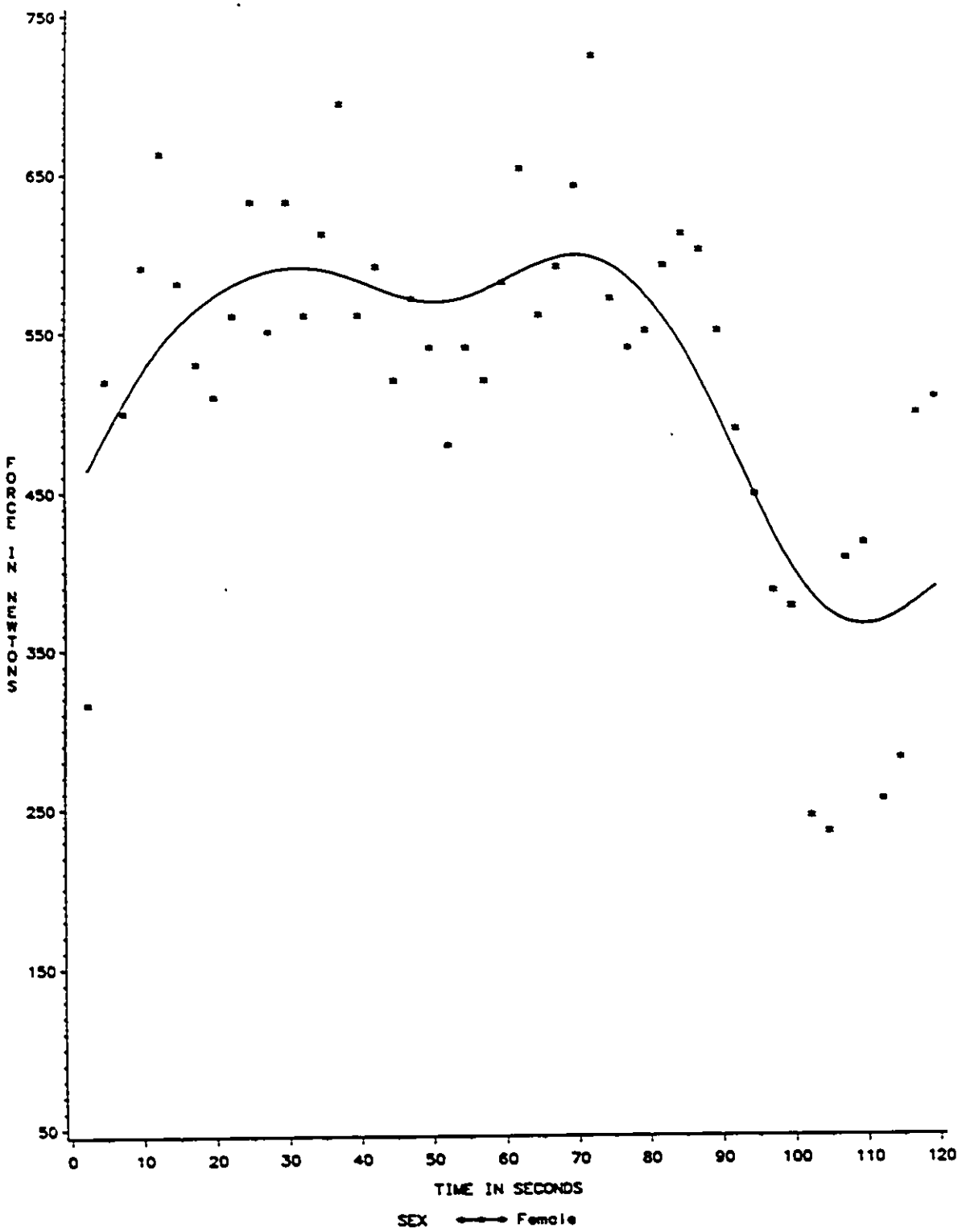

INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=11
750
650
550
450
350
250
150
50
FORCE IN NEWTONS
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Female


INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=12
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Female


INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=13
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Female

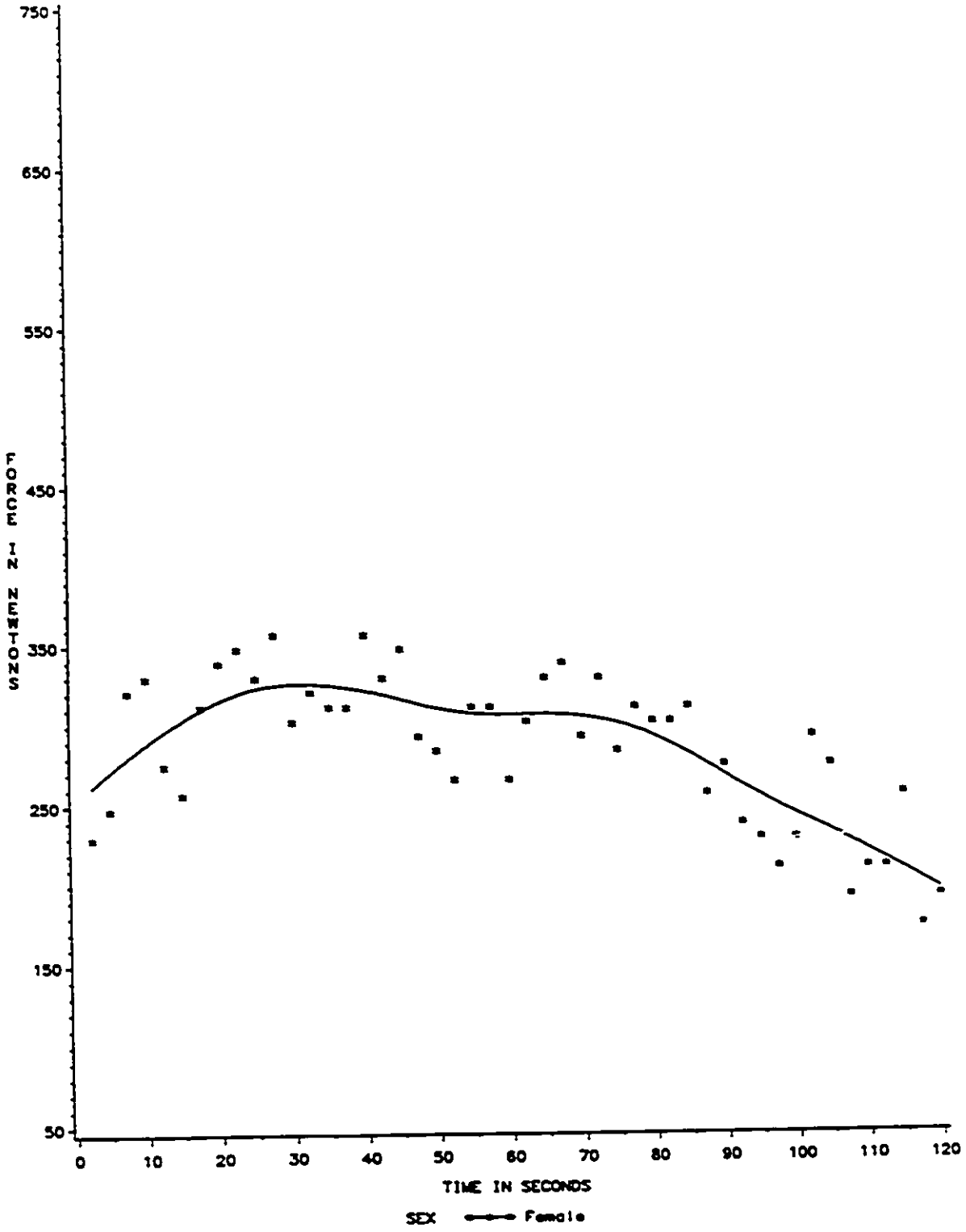
INDIVIDUAL ROLLERBOARD FORCE VALUES

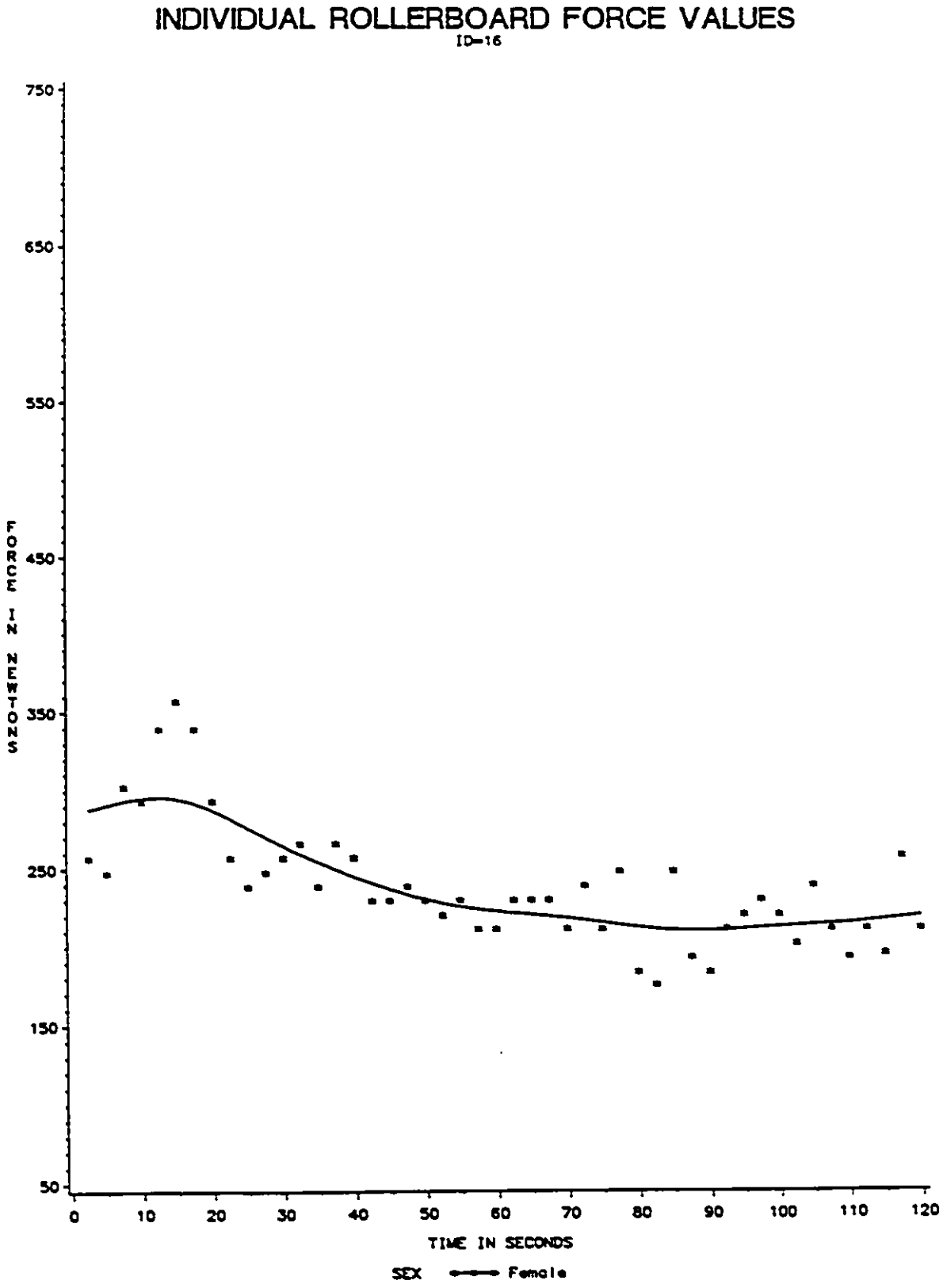
ID=14



INDIVIDUAL ROLLERBOARD FORCE VALUES

ID=15




INDIVIDUAL ROLLERBOARD FORCE VALUES
ID=16
FORCE IN NEWTONS
750
650
550
450
350
250
150
50
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME IN SECONDS
SEX
Female

INDIVIDUAL ROLLERBOARD FORCE VALUES

ID=17