THE MAXIMAL SHORT TERM POWER OUTPUT OF HUMAN LEG MUSCLES DURING ISOKINETIC CYCLING EXERCISE

by

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"A great deal of the research by physiologists on exercise has concentrated on the fuel intake (O_2 consumption) rather than the resulting output of mechanical power which is the truly useful product."

D. R. Wilkie, 1980

ABSTRACT

Classical force-velocity studies by A. V. Hill demonstrated that there was an optimal velocity for maximal power output of isolated muscles and human movements. Thus to study muscle performance during maximal dynamic exercise it is important to measure mechanical power output at several constant velocities of movement. At the start of this work no instruments were available to measure maximal power during isokinetic movements over a wide range of velocities. For this reason a cycle ergometer (CVE) was developed which restricted the crank velocities to chosen upper limits, despite maximal efforts by the subject.

Measurements were obtained in male subjects of maximal peak torque generated over 81% of the functional range. There was a consistent inverse linear relationship between peak torque and crank velocity, and the results were reproducible from day to day. Considerable inter-subject variability in peak torque was accounted for only partly by differences in thigh muscle volume. Maximal peak power occurred at various crank velocities ranging from 120 to 160 rpm; differences in muscle fibre types may have contributed to the variation observed. Maximal power occurred when the force equalled 0.3 to 0.4 of the predicted maximal isometric tension, in agreement with Hill's studies.

Torque, work and power were also measured during 30 s of maximal effort at 60, 100 and 140 rpm. Increases in crank velocity were associated with both a higher initial power, and a greater rate and extent of decline in power, but total work was similar. The greater decline at faster velocities may reflect differences in energy metabolism, or motor unit activation. In addition to defining the effects of velocity on maximal power output in healthy young subjects, the studies showed the CVE to be a sensitive, reliable instrument, with potential applications to the assessment of human muscle function in health and disease.

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1. HISTORICAL OVERVIEW

1.1 Introduction

The relationship between force, speed of movement, and the concomitant work output and efficiency of human muscle was the subject of considerable investigation during the early 1900's. In a classical paper on the mechanics of human muscle A. V. Hill (1922) discussed these factors as they pertained to maximal voluntary isotonic contractions of the elbow flexors (Fig. 1). He demonstrated that as the speed of movement (v) increased, the work (W) done decreased linearly according to the equation $W = Wo - kv$, where Wo is the muscle's mechanical potential energy, and k is a constant "varying as the coefficient of viscosity of the muscle fluids". Since the distance moved by the arm was always the same, the force exerted by the muscles varied directly with the work. This linear relation was shown theoretically to result in an optimum speed of movement at which the mechanical efficiency (external work done/energy used up) was greatest. The calculated maximum mechanical efficiency of approximately 26% occurred when the contraction occupied one second. A comparatively small decrease in the contraction time resulted in a marked loss of efficiency, whereas a relatively large increase in the time caused a much smaller loss.

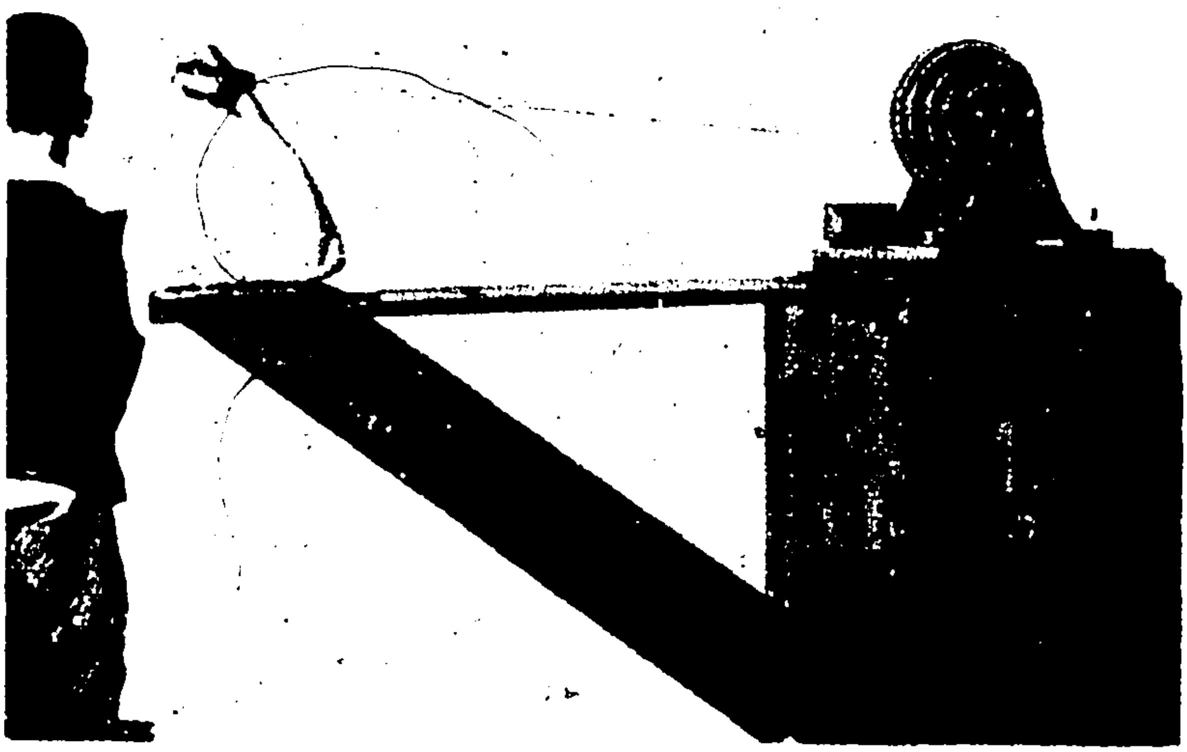
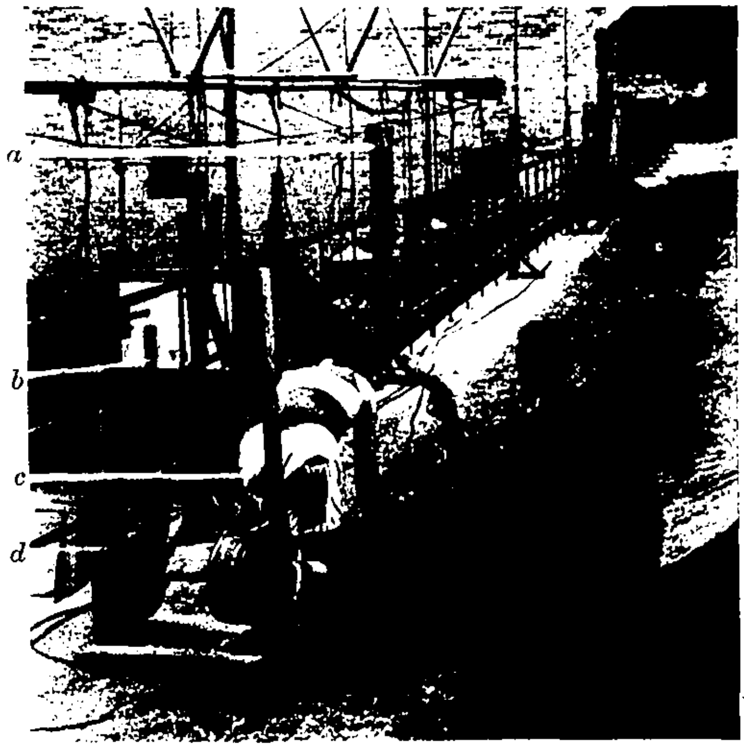


Figure 1. The inertia wheel apparatus used by A. V. Hill (1922) to measure the maximum work capacity of the human elbow flexors.

In a follow-up study in the same laboratory Lupton (1922) measured more precisely the time occupied in maximal arm flexions and the subsequent work output, and was able to confirm the validity of Hill's equation. Thereafter the linear relation established in human arm movements between force exerted and speed of movement was found to be equally applicable to activities involving the legs. Furusawa, Hill and Parkinson (1927a) suggested that it could explain the acceleration of a runner, and set a limit to his maximum running speed. Best and Partridge (1928) confirmed the prediction in an experiment in which external resistances of varying magnitude were added to a runner (Fig. 2). A constant external resistance caused a reduction in maximum running speed which was equal to that calculated from the equation of Furusawa, Hill and Parkinson. Dickinson (1928) determined the maximum speed of pedalling a cycle ergometer as a function of the resistance applied to the wheel. Once again the relation between maximum speed and load proved to be linear, the speed decreasing as the load increased according to Hill's (1922) earlier equation.

Hill (1922) calculated that a linear relation in human muscle between speed and force must result in an optimum rate for the attainment of peak mechanical efficiency. Several studies were published reporting results which corresponded very closely to Hill's theoretical values.



a, Recording coil; *b*, Spring balances; *c*, Cord from capstan to runner's waist; *d*, Linen friction band.

Figure 2. The experimental design used by Best and Partridge (1928) to record sprinting performance with various external resistances imposed on a runner.

Using a variable speed ergometer, Cathcart, Richardson and Campbell (1923) determined from measures of oxygen consumption that the highest efficiency for alternating arm movements was between 23 and 24.7%, occurring when the duration of a single contraction varied from 0.7 to 1.0 second. Lupton (1923) on the other hand, reported a maximum efficiency of 26.7%, at an optimum contraction duration of 1.36 seconds, when the activity required a simultaneous contraction of the flexors of both arms. The peak efficiency during pedalling on a cycle ergometer proved to be 21.8%, coincident with a contraction duration of 0.9 seconds (Dickinson, 1929), whereas in stairclimbing the respective values were 24.4% and 1.36 seconds (Lupton, 1923). In every study the curve relating efficiency to duration of contraction was of the same general shape and dimensions as that calculated by Hill (1922). At the time it was commonly believed that these phenomena associated with muscles shortening against a load could be explained by the "visco-elastic" theory of muscle contraction.

1.2 The Visco-Elastic Theory of Muscle Contraction

In 1892 Adolph Fick published a paper in which he concluded that it was the actual process of muscle shortening under tension which was largely responsible for the expenditure of chemical energy. However, this conclusion was refuted by A. V. Hill (1913) who determined that an isolated frog's muscle suddenly allowed to shorten (without load) from the point of peak isometric tension, produced no more heat than if shortening was prevented. This indicated that there was no additional chemical energy liberated in the muscle specifically associated with the process of shortening. Thus it appeared that when stimulated a muscle acted like a stretched spring, possessing elastic potential energy. During shortening some of this energy could be recovered as external work, the rest being dissipated in "overcoming the viscous resistance of the muscle to its change of form" (Hill, 1922). The viscosity was believed to increase in proportion to the velocity of shortening, hence during rapid movement more of the mechanical potential energy would be lost as heat and less would be manifest as external work. Efficiency would be determined by a balance between the viscosity of the muscle, and the energy necessary to maintain the contraction long enough to allow the generation of an adequate amount of work (Hartree and Hill, 1928). In support of this argument Hartree and Hill (1928) demonstrated that comparatively much more energy was required for the maintenance of contraction in isolated frog muscle than in man, which explained why the greatest efficiency in frog muscle occurred during contractions of considerably briefer duration.

1.3 The Two Component Model of Muscle Contraction

The linear relation existing in man between force exerted and speed of movement could be explained satisfactorily by the visco-elastic model, and it was widely accepted. However, studies of isolated muscle gradually produced results which first cast grave doubts on the validity of the theory and eventually brought about its dismissal.

The first study of major importance was the elegant work of Fenn (1923), in which he compared the energy liberated and the work performed by the isolated sartorius muscle of the frog. The evolution of heat was measured during maximal isometric tension, and in isotonic contractions during which the muscle was required to (i) lift increasing weights through a constant height, (ii) lift the same weight through increasing heights, (iii) do work on an inertia lever which allowed both the tension and the extent of shortening to vary simultaneously. In contrast to some of the older studies on the structurally more complex gastrocnemius muscle, Fenn demonstrated conclusively that the sartorius muscle's heat production under isometric conditions was less than in any contraction where shortening was allowed. Moreover, the increase in heat above the isometric was directly proportional to the work done, irrespective of whether it was the tension or the amount of shortening that was varied. The "Fenn effect" was proof that the shortening of a muscle was an active, energy consuming process, and could not be represented adequately by the recoil of a stretched elastic body. Adolph Fick's earlier (1892) contention was thus substantiated.

Despite Fenn's definitive evidence, the visco-elastic theory took "like Charles II, an unconscionable time dying" (Hill, 1970). In 1924 Gasser and Hill were intent on verifying in isolated frog muscle the linear relationship Hill (1922) had established in human arm muscles between speed of movement and work performed. It was readily established that when frog muscle was stimulated to produce peak isometric tension and then suddenly allowed to shorten a given distance, the work done was proportional to the equivalent mass and therefore inversely related to the speed. However, it was not a simple linear relation. It would be realized later that Gasser and Hill had almost discovered a fundamental property of muscle, its force-velocity characteristic. However, at the time they were "hypnotized by the obvious importance, in man, of relating energy used to mechanical work performed at varying speed" (Hill, 1970), and consequently did not realize the significance of their findings. Once again the results were deemed compatible with the visco-elastic model.

A further study which cast doubt on the visco-elastic theory was by Levin and Wyman (1927), who published observations on the tension produced by isolated muscle allowed to shorten at a set rate on their constant velocity ergometer. The expected linear relation between work and speed of shortening proved to be almost hyperbolic, and the authors suggested that their results were compatible with a muscle containing both an undamped non-contractile element, and a damped contractile element. Only the damped elastic component appeared to act in accordance with Hill's (1922) equation.

While delivering the Croonian Lecture to the Royal Society of London on May 20, 1926, A. V. Hill commented that "the alteration of force exerted with velocity of shortening is a fundamental characteristic of muscle, varying with the function which it has to fulfil, and supplying an important clue as to its ultimate physico-chemical mechanism". Despite this contention, and the data of Fenn (1923), Gasser and Hill (1924), Levin and Wyman (1927), it was not until 1935 that Fenn and Marsh published the first systematic analysis of the force-velocity relationship in isolated muscle.

1.4 The Force-Velocity Relation in Isolated Muscle

By 1934 there was considerable support for Levin and Wyman's (1927) hypothesis that a contracting muscle behaved as a two component system, containing contractile and non-contractile elements in series. Fenn and Marsh (1935) reasoned that this being the case, then it should be possible to study the mechanical properties of the contractile component alone by observing the speed of isotonic shortening under different loads; a condition in which the undamped non-contractile element would be previously stretched, and therefore excluded from participating further in the mechanical events of shortening. Experiments were performed on the sartorius and gastrocnemius muscles of the frog, and the gastrocnemius muscle of the cat; stimulation was either direct, or indirect via the appropriate nerve. The muscle was stimulated to lift a wide range of loads and the maximum speed of shortening recorded, always at the same muscle length. As Levin and Wyman (1927) had reported earlier, the relation between force exerted and velocity of shortening was not linear, being almost logarithmic in nature. Moreover, the velocity of shortening increased with increasing temperature, which suggested that it was associated with the kinetics of underlying chemical reactions, rather than representing the fixed response of a simple mechanical system.

Three years later A. V. Hill (1938) performed a series of experiments on the heat production and mechanical properties of isolated frog sartorius muscle during isotonic shortening (Fig. 3). The results indicated a similar force-velocity relation to that reported by Fenn and Marsh (1935), but which could be described by the equation of a rectangular hyperbola: $(P + a)(V + b) = (Po + a)b$ where P is force, V is velocity of shortening, Po is maximum isometric tension, a and b are constants with the dimensions of a force, and velocity, respectively (Fig. 4). Measurements of the heat production during isotonic contraction revealed that when a muscle shortened, in addition to the "Fenn effect", it liberated energy for shortening proportional to the shortening. Moreover, the rate of energy liberation (above isometric) was an inverse linear function of the load: $(P + a)V = b(Po - P)$ where a is the shortening heat per centimetre of shortening. This demonstration that the empirical constants derived from the force-velocity relation were the same as those obtained by thermal measurements, lent considerable support to the hypothesis that the speed of contractile element shortening under a load was determined by the manner in which energy liberation was regulated (Fenn and Marsh, 1935). The muscle could be represented no longer as a stretched spring working in a viscous medium.

Hill's (1938) characteristic equation has since been applied successfully to isolated toad (Hill, 1949) and tortoise (Katz, 1939; Woledge, 1968) muscle, and to a variety of muscles from mammals such as the mouse (Close, 1965), rat (Ritchie, 1954; Close, 1964; Wells, 1965) and

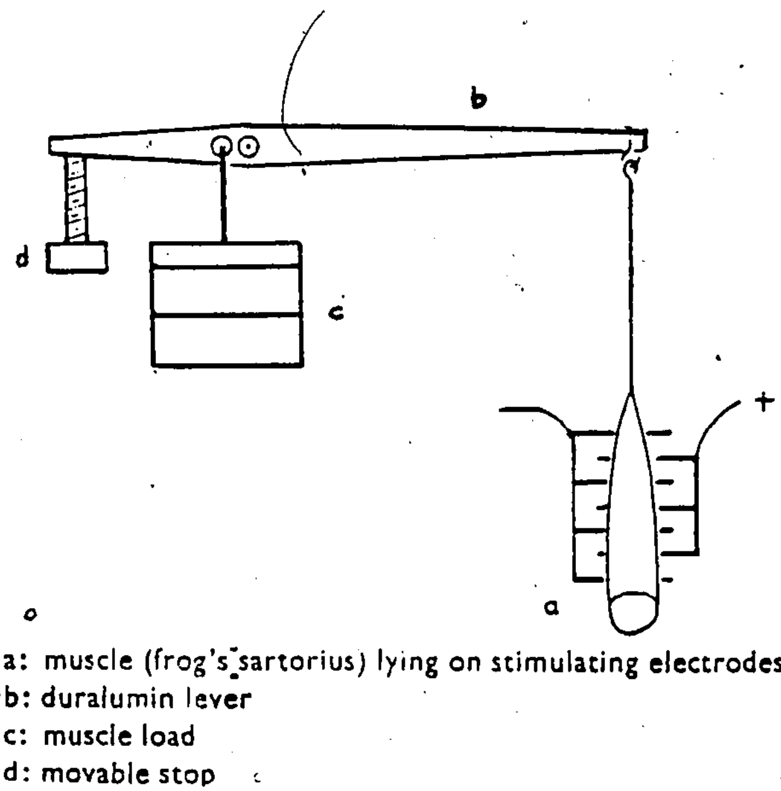


Figure 3. The conventional apparatus to measure dynamic properties of isolated skeletal muscle. Adapted from: Wilkie, D. R. (1956). The mechanical properties of muscle. Brit. Med. Bull. 12:177-182.

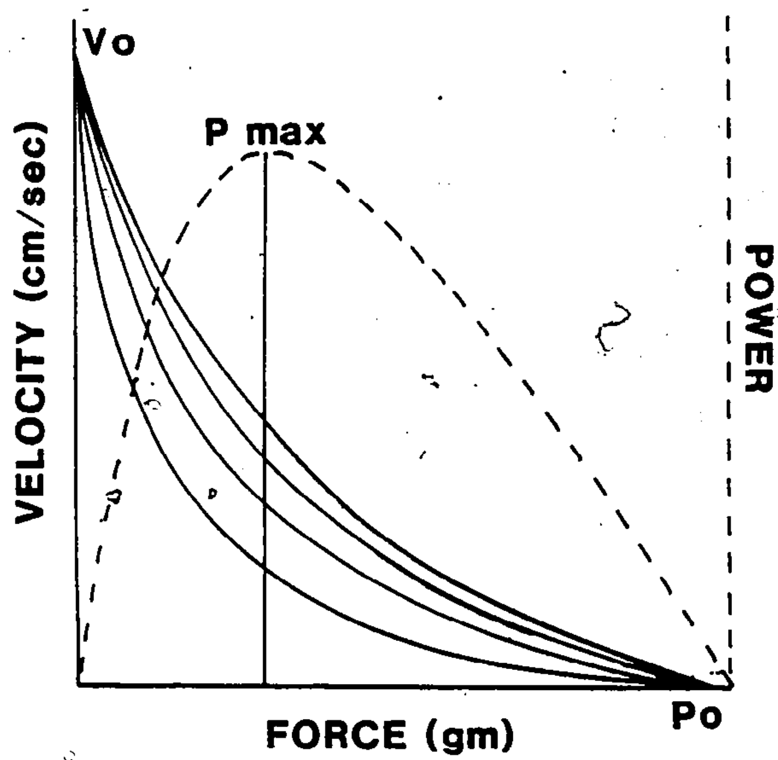


Figure 4. A series of force-velocity curves obeying Hill's characteristic equation. Vo is the maximal velocity of shortening with zero load; Po represents maximal isometric tension. From left to right the curves are described by a/Po = 0.1, 0.2, 0.3 and 0.4. The constant a has the dimensions of a force (a g.cm being the "extra heat" produced for 1 cm of shortening). Power is calculated for the curve with a/Po = 0.2; maximal power occurs when P/Po is approximately 0.3.

Adapted from Binkhorst, R. A., L. Hoofd and A. C. A. Vissers (1977). Temperature and force-velocity relationship of human muscles. J. Appl. Physiol. 42:471-475.

cat (Fenn and Marsh, 1935). It also appears applicable to isolated bundles of human muscle (Faulkner, Jones, Round and Edwards, 1980), and satisfactory curves have been obtained in papillary muscle isolated from cat heart (Sonnenblick, 1962).

The curvature of Hill's (1938) force-velocity curve is described by the ratio a/Po, which is generally about 0.25 (Fig. 4). An interesting exception however, is the force-velocity curve of tortoise muscle. In 1939 Katz reported that the force-velocity curve of tortoise retractor penis muscle was considerably more curved than that of frog muscle, and could only be fitted by Hill's (1938) equation with a value of a/Po ranging from 0.07 to 0.16. Although no direct measurements of heat production were made, the shape of the curve predicted less overall heat generation and a greater efficiency in tortoise muscle. Woledge (1968) tested this hypothesis and found it to be correct; the maximum ratio of work/enthalpy liberation during shortening, and the efficiency for the overall cycle of contraction and relaxation in tortoise muscle, was 70% greater than in frog muscle. Woledge did not believe that the slowness of tortoise muscle could explain its greater efficiency and he proposed a mechanism associated with the cycling of cross bridges between the myofilaments (after Huxley's sliding filament model, 1957).

1.5 The Force-Velocity Relation in Fast and Slow Muscle

In 1873 Ranvier published the first experimental evidence that red muscles in the rabbit tended to contract more slowly than their white colleagues. It is now firmly established that muscle fibres can be classified into two, and perhaps three functional types on the basis of morphological, histochemical and contractile properties (Burke, et al, 1973). Common nomenclature is slow twitch oxidative (Type I), fast twitch oxidative glycolytic (Type IIa), and fast twitch glycolytic (Type IIb). In this thesis fibre types will be referred to as either Type I or Type II.

The force-velocity behaviour measured in a whole muscle taken from an adult rat was influenced by the relative proportion of Type I and Type II fibres comprising its makeup; the speed of shortening at any given load was greater for fast muscles than slow ones (Wells, 1965). Similarly, in isolated bundles of human muscle fibres the maximal velocity of shortening, and the force exerted at any contractile speed was greater the higher the percentage of Type II fibres (Faulkner, Jones, Round and Edwards, 1980).

The histogenesis of striated muscle in mammals results in the formation of limb muscles that are uniformly slow at first (Close, 1972), and much attention has been focused on the dynamic properties of developing muscle. Close (1964) provided a detailed description of the force-velocity relation in rat fast muscle, the extensor digitorum longus (EDL), and slow muscle, the soleus (SOL), at various stages of development from birth to 100 days. Speed of shortening was expressed precisely as the velocity/1000 sarcomeres length of muscle fibre, and the load as a fraction of the maximal isometric tension (Po). At birth the force-velocity properties of EDL and SOL were very similar, but during development the speed of shortening/sarcomere, for any given fraction of Po, increased threefold in EDL whereas in SOL there was no significant change. Similar differences between the EDL and SOL muscles of new-born kittens and adult cats led Close (1967) to postulate that differentiation of mammalian muscles into fast and slow types may be attributed to an increase of shortening speed of the fast muscles. Subsequent work (Close, 1969) reported that the differences in intrinsic speed of shortening in EDL and SOL in adult rats could be reversed by cross-innervation, thus implicating the nervous system in the determination of muscle contractile properties.

In Hill's original experiments (1938) the similarity between the empirical constant "a" derived from mechanical measurements, and the coefficient of shortening heat, suggested that the velocity of isotonic shortening at any given load was governed by the rate of energy liberation within the muscle. In his final treatise on the subject Hill

(1964a) demonstrated that the two constants were not identical, although the resemblance between them inferred that they were connected in some way. The characteristic equation was modified such that the rate of extra energy liberation during shortening was equal to $(P + \alpha)$, where P is force and α is the coefficient of shortening heat. There is now considerable evidence that the speed of shortening (hence the rate of extra energy liberation within the muscle) is related to the specific activity of the Mg^{2+} ATPase, and the actin-activated ATPase of myosin. The close correlation between speed of shortening and myosin ATPase activity has been found in a variety of muscles from mammals, lower vertebrates, and invertebrates (Barany, 1967). Moreover, when the contractile properties of fast and slow twitch muscles in the cat were reversed by cross-innervation, the myosin ATPase activities were found to change in an identical manner (Buller and Mommaerts, 1968).

It is possible that the underlying causes of the force-velocity characteristics of muscle are as yet incompletely understood, but the current view is that it is "a direct consequence of the mechanochemical coupling between the stress in the contractile elements and the rate of the energy yielding reactions that accompany contraction" (Carlson and Wilkie, 1974).

1.6 The Force-Velocity Relation in Human Muscle

Hill's (1938) demonstration that the force-velocity behaviour of isolated frog muscle could be described as a rectangular hyperbola led investigators to search for a similar relation in human muscle, in vivo. It is appropriate that the first application of the characteristic equation to human muscular movement was by A. V. Hill (1940) himself. In an investigation of the dynamic constants of human muscle he critically reviewed the earlier inertia wheel results of Lupton (1922), and Hill (1922). Hill's characteristic equation was deduced from experiments on isolated frog muscle stimulated to shorten under a constant load. To make the equation applicable to human muscles in vivo it was modified to account for a constant mass accelerated, and corrected for the inertia of the forearm. Subsequently, the results were indeed compatible with a hyperbolic force-velocity relationship similar to that in isolated frog muscle.

In 1947 Dern, Levene and Blair attempted to extend Hill's earlier (1940) work to cover a wider range of forces and velocities, in order to provide a more rigorous test of the characteristic equation to human muscle. An isotonic lever apparatus was used to provide either a wide range of constant torques about the elbow joint, or linear forces, during maximal voluntary flexions of the forearm. The experiments employing linear forces did result in hyperbolic force-velocity curves although not as curved as in frog muscle, a/Po ranging from 0.43 to 0.63. Moreover, electromyography indicated considerable activity in antagonist muscles which meant that the measured forces were resultants, and therefore lower than the true tension in the agonist. It was concluded that co-contraction of the antagonists defied any interpretation in terms of the force-velocity behaviour of individual muscles.

Three years later Wilkie (1950) also investigated the relation between isotonic force and velocity of movement in maximal flexions of the elbow. The contractions were afterloaded by a series of known weights, and velocity was the velocity of the hand measured at the end of each movement. Initially the data could not be fitted by the characteristic equation, except at tensions greater than 0.3 Po. However, when a mathematical correction was made for the inertia of the forearm, the in-vivo muscles displayed the same force-velocity behaviour as isolated frog muscle. The values of a/Po from 0.2 to 0.48 were considerably lower than those found previously by Dern, Levene and Blair (1947), a discrepancy that Wilkie attributed to Dern's failure to correct for inertia of the forearm. Another difference between the two studies was that Dern detected activity in antagonist muscles whereas Wilkie did not.

1.7 Isokinetic Accommodating Resistance Exercise

There is a marked difference in the resistance imposed by an isotonic load in an isolated muscle preparation, and during human muscular movement. In the isolated preparation a constant load presents a uniform resistance to the muscle throughout shortening. When a human performs an isotonic contraction however, the resistance opposed to the muscle is modified by the constraints of the limb lever system. In the middle range the lever is most efficient and the load on the muscle is considerably less than it is at the extremes of range. Consequently, the tension in the muscle during isotonic contraction is maximum during a relatively small range of movement, and the work done is accordingly submaximal (Hislop and Perrine, 1967). Maximum work output can only be achieved when the muscle is opposed throughout shortening by a resistance which it is just able to overcome (Hill, 1922). This criterion is satisfied by the relatively new technique of isokinetic accommodating resistance exercise (Hislop and Perrine, 1967). An isokinetic instrument affords a means of maintaining the speed of limb movement constant at a predetermined rate, despite maximal muscular effort by the subject; resistance therefore varies in proportion to the force exerted. The majority of recent studies of force-velocity characteristics in intact human muscle have been performed using an isokinetic system; force is usually acting about an axis of rotation and expressed as torque. It is worthwhile mentioning that in isolated muscle it is also possible to control the rate of shortening and measure the maximal force output, to obtain satisfactory force-velocity curves (Hill, 1970).

The most commonly used isokinetic device to measure muscle force output is the Cybex (Lumex Inc., New York). Early studies confirmed that the apparatus transmitted torque accurately through 180° at speeds up to 4 rpm (i.e. 4 x 360°/60 = 24°/sec) (Moffroid et al, 1969). Peak torque generated at 65° of knee extension was measured in thirty male subjects at speeds from 0 to 18 rpm, and the relation was linear over the fastest one third of the range. However, at slower angular velocities (0 - 6 rpm) the torque decreased in a curvilinear manner, in marked contrast to the behaviour of isolated muscles.

Thorstensson, Grimby and Karlsson (1976) extended the range of testing to include speeds up to 30 rpm (180°/sec), and claimed to demonstrate a force-velocity relationship which was compatible with Hill's (1938) original findings in isolated frog muscle. However, the angle specific values of peak torque presented in their table 1 are not represented accurately in their figure 2, and the curve does not reflect torque generated at a specific knee angle. For these reasons the study has been heavily criticized (Perrine and Edgerton, 1978; Gregor et al, 1979). Similar limitations apply to the study of Ingemann-Hansen and Halkjaer-Kristenson (1979), which also reported a classical hyperbolic relation between peak torque produced by the knee extensors and angular velocity of movement up to 60 rpm (360°/sec).

It seems that when the torque generated at a given velocity is measured at a specific joint angle there is agreement with the earlier conclusions of Moffroid et al (1969), that the in vivo torque-velocity curve plateaus at low velocities. During maximal knee extensions at velocities less than 16 rpm (96°/sec) the peak torque capacity may even decline by 4 to 5% as it approaches Po (Perrine and Edgerton, 1978). This phenomenon may be attributed to either the physical discomfort associated with maximal isometric exercise, hence an incomplete activation of the motorneuron pool (Perrine and Edgerton, 1978), or an increased Golgi tendon organ inhibition, which would be more pronounced at lower velocities where force is greater.

A major limitation of the Cybex isokinetic device is the relatively narrow range of velocities that can be achieved. Testing is often restricted to approximately 26% of the subject's maximal attainable velocity with zero load (Thorstensson, Grimby and Karlsson, 1976), and can never be much higher than 50% (Coyle, Costill and Lesmes, 1979). Consequently, a torque-velocity characteristic derived in this manner is only representative of the high torque, low velocity portion of the curve. Furthermore, the peak torque recorded at the highest velocities may not reflect accurately the highest tension produced in the muscle. During rapid movement there may be a considerable delay before the limb segment accelerates to attain the preset angular velocity of the instrument's lever arm. The skeletal lever may be beyond the point of optimal mechanical advantage before the muscle can generate maximal tension, and thus the peak torque occurs progressively later in the range with increasing speeds (Moffroid et al, 1969). Another distinct weakness of the Cybex instrument is the acknowledged "impact" (Winter et al, 1981) or "overshoot" artifact (Sapega et al, 1982), that results in increasingly spurious estimates of peak torque at high velocities of movement. Sapega et al (1982) recently demonstrated during hip abduction movements that in the initial catch-up phase before resistance was encountered, the velocity of the limb-lever system may exceed the pre-set velocity by as much as 200%. Sudden resistance caused deceleration of the limb-lever system and a concomitant initial torque spike which overestimated true muscular torque by up to 115%. The situation was further complicated by a greater degree of post-engagement overspeeding at faster angular velocities. Finally, there is evidence that at faster speed settings of the Cybex lever arm a given torque input to the system results in a progressively higher voltage output; as angular velocity increases from 0 to 30 rpm (180°/sec) peak external torque may be overestimated by up to 20% (Olds et al, 1981). It has been suggested that separate torque calibrations should be performed for each velocity (Murray, Harrison and Wood, 1982).

Recently, the principle of isokinetic resistance has been applied to dynamic exercise on a cycle ergometer (Sargeant, Hoinville and Young, 1981). A constant angular velocity was achieved by an electric motor driving the pedal cranks and a variable gearing system enabled testing to take place over a very wide range, from 23 to 171 rpm (138 to 1026°/sec). One striking feature of the results was the extremely linear relation between force exerted and angular velocity of the pedal assembly. Failure to demonstrate a plateau of force as in other studies may have been due to mechanical constraints, which prevented testing at comparable low speeds.

There is one major potential weakness in the ergometer used by Sargeant, Hoinville and Young (1981). The cranks are driven at a constant velocity by the motor, and the subject attempts to exert maximal force on the moving pedal assembly. Consequently, at fast speeds the action of antagonist muscles may actually oppose the forward movement of the pedals and the contractions may become increasingly eccentric. Furthermore, it may also be difficult to distinguish between the torque produced by the passive weight of the leg on the pedal and the torque generated by the active muscles.

1.8 The Maximal Power Output of Human Muscle

It was originally determined by A. V. Hill (1922) that a hyperbolic or linear relation between force exerted and velocity of human movement must result in an optimal velocity for maximal mechanical power output (optimal in frog muscle when P/Po = 0.3, Hill, 1964c). For intense efforts of short duration it is therefore essential that load and speed are matched precisely to the properties of the particular muscles under test (Wilkie, 1960). However, there have been no systematic investigations of maximal short-term exercise which have adhered to these principles. In studies of short-term exercise maximal power has been calculated during running, jumping, rowing, cycling, and during isokinetic contractions.

1.8.1 Maximal Power Output in Running

The external mechanical power output during running is largely associated with overcoming air resistance, and is very small compared to the power dissipated within the body (Furusawa, Hill and Parkinson, 1927a). In sprinting 100 yards a runner may generate 8.5 horsepower at his maximum velocity of 11.46 yards a second (Furusawa, Hill and Parkinson, 1927b), but as little as 0.16 horsepower may be manifest as external work (Fenn, 1930). An added resistance may double the external power (Best and Partridge, 1928), but it is clear that most of the power developed during running cannot be measured directly.

Running uphill offers a more suitable method of estimating external power output; maximal values of 1.32 and 0.94 horsepower maintained for 4 and 30 s respectively, have been reported (Unna, 1946). The calculation of external power during stairclimbing has gained widespread acceptance, and maximal levels of greater than 1.5 horsepower may be generated for a very brief time (Margaria, Aghemo and Rovelli, 1966).

1.8.2 Maximal Power Output in Vertical Jumping

Vertical jumping from a force platform has been employed to assess the power output of the body during a single movement, lasting for less than one-fifth of a second (Davies and Rennie, 1968; Asmussen, Bonde-Peterson and Jorgenson, 1976). Values for maximal instantaneous power in 47 healthy young men were as high as 5.23 horsepower (3902 watts), and for women, 3.15 horsepower (2350 watts) (Davies and Rennie, 1968). These figures are in close agreement with the theoretical limit for any practicable movement (Wilkie, 1960).

A common problem associated with the calculation of mechanical power in running and jumping is that in neither case is the load suitably matched to the muscles "so as to exploit to the full their intrinsic force-velocity relationship" (Wilkie, 1960). Both activities involve rapid acceleration, so the shortening velocity of the muscles cannot remain for long at its optimum.

1.8.3 Maximal Power Output in Rowing

The force output during maximal effort is dependent upon the absolute muscle mass involved in the activity. During the pull stroke in rowing the extensors of the trunk and legs and the flexors of the arms are working maximally and it might be expected that the greatest external power output would be attained in this exercise. This is true as long as the activity is maintained for several minutes. Olympic champion oarsmen may maintain 0.57 horsepower for 6.25 minutes, rowing at a speed of 12 miles per hour (Henderson and Haggard, 1925). However, during brief bouts of maximal effort made at high frequency there is a large waste of energy from acceleration and deceleration of the body, and the external power output is less than predicted theoretically (Wilkie, 1960).

1.8.4 Maximal Power Output in Cycling

Cycling has distinct advantages over most other activities for the measurement of mechanical power. The gearing can be adjusted to allow the work to be performed at a variety of relatively constant speeds, and maximum use can be made of the kinetic energy of the moving limbs (Wilkie, 1960). Consequently, cycle ergometers are used extensively in both research and clinical laboratories to assess aerobic power and endurance capacity. However, less attention has been directed to the assessment of maximal power output in bouts of pedalling lasting for less than one minute, a period of time in which the muscles should theoretically be dependent mainly on anaerobic energy sources (Margaria, Ceretelli and Mangili, 1964).

Most direct studies of maximal power output during cycling have measured the time taken to perform a fixed amount of work, while pedalling at maximal velocity. Asmussen and Boje (1945) reported that 9.38 kJ of work could be performed in 11.5 to 14.4 seconds, resulting in mean power output ranging from 651 to 815 watts (0.87 to 1.09 horsepower). When a considerably greater frictional resistance was applied to the flywheel, Bergh and Ekblom (1979) noted that 8.5 kJ of work could be completed in 10.7 to 15.3 seconds, at an average rate of 557 to 730 watts (0.75 to 0.98 horsepower). These values are substantially lower than the

1.3 to 1.7 horsepower which Nonweiler (1958) calculated during world record sprint performances by champion racing cyclists. However, they are in close agreement with the maximal forces exerted at various phases of normal cycling (Soden and Adeyefa, 1979).

A test which lasts for 30 seconds and has gained widespread popularity is the Wingate Anaerobic Capacity Test (Bar-Or, 1978). In this procedure the subject pedals as fast as possible against minimal resistance (thereby overcoming the inertial resistance of the flywheel) which is increased to a predetermined level within a few seconds. The number of pedal revolutions is then monitored for 30 seconds, and the work calculated for successive five second intervals. Typical power output values for a five second period range from 700 to 800 watts at the start of the test, to 200 to 300 watts at the end. Total work may be 15 to 16 kJ, corresponding to a mean average power of 500 to 533 watts.

It appears that cycling is a superior technique for measuring mechanical power output than running, jumping or rowing, but it shares the same inherent limitation when applied to maximal efforts of short duration. During steady-state submaximal work the rate of pedalling is approximately constant, and the frequency may be adjusted to obtain the greatest efficiency. However, during a maximal effort the subject pedals as fast as possible against a constant resistance, and the frequency of pedalling decreases rapidly throughout the test. Consequently, the shortening velocity of the active muscles cannot remain for long at the optimum point on their intrinsic force-velocity curve. Furthermore, the maximal power output capacity at different pedalling frequencies cannot be measured.

An ergometer has been designed which allowed both force and speed to be freely adjusted (Osborne, Read and Wilkie, 1975), and a constant power of approximately 650 watts could be maintained for 30 seconds (Wilkie, 1980).

Data from an isokinetic ergometer which allowed the forces transmitted across the cranks to be monitored continuously (Sargeant, Hoinville and Young, 1981) at a variety of speeds, indicated that 110 rpm was the optimum speed for the generation of maximal power output. Instantaneous peak power, and maximal average power in a complete revolution were 1387 and 840 watts respectively, whereas the mean power during a 20 second test was 665 watts. The ergometer of Sargeant, Hoinville and Young (1981) appears to be the best available for absorbing the true maximal power output of the legs, but it does have the major limitation discussed previously.

1.8.5 Maximal Power Output in Isokinetic Contractions

Isokinetic devices such as the Cybex possess the major advantage that the angular velocity of the instrument's lever arm can be maintained constant at a chosen level, and the maximal force generated during single-joint movements can be measured. However, because of mechanical limitations the testing is restricted to the high torque, low velocity region of the torque-velocity curve. Moreover, at the highest speeds there appear to be major problems in obtaining an accurate measure of torque. For these reasons the majority of isokinetic devices may not be sufficiently versatile to allow a true recording of maximal power output.

Most studies of torque capacity during isokinetic contractions have concentrated on the knee extensor group of muscles during single-leg movements. Maximal angular velocities of the lever arm ranged from 180 to 288 degrees per second (30 to 48 rpm), and instantaneous peak power from approximately 408 (Thorstensson, Grimby and Karlsson, 1976; Larsson, Grimby and Karlsson, 1979) to 680 watts (Perrine and Edgerton, 1978). Average power output is very low, and not generally reported.

It is apparent that an isokinetic system using short range movements (e.g., as usually performed on the Cybex) is not as appropriate for allowing the generation or measurement of maximal power output as an isokinetic system using the bicycling movement.

1.9 Muscle Fibre Types, Muscle Bulk, and Maximal Power Output

Many studies of isokinetic exercise have investigated the relationship between torque production at various angular velocities and the percent as well as relative area of Type II fibres in the contracting muscle. Thorstensson, Grimby and Karlsson (1976) were the first investigators to report a significant positive relationship between peak instantaneous power generated at the fastest angular velocity of the lever arm (180°/sec), and the percentage of Type II fibres in the knee extensor muscles. This correlation has since been confirmed in athletes (Gregor et al, 1979; Thorstensson, 1976) and non-athletes (Coyle, Costill and Lesmes, 1979). Such data are in accordance with the contractile properties of isolated animal (Wells, 1965) and human (Moulds, Young, Jones and Edwards, 1977; Faulkner, Jones, Round and Edwards, 1980) muscle, and the empirical observations on muscle fibre types in athletes and sedentary individuals (Gollnick et al, 1972).

Not only the muscle fibre type distribution, but also the absolute quantity of muscle may be important in determining the external force generation (Ikai and Fukunaga, 1968). Indeed, differences in muscle (and bone) volume were shown by Sargeant, Hoinville and Young (1981) to account for most of the variation in force-velocity behaviour in their group of subjects, who were homogeneous in fibre type. When any measurements of muscle force are recorded it is therefore important to standardize the data in relation to either the greatest cross-sectional area, or the overall muscle bulk (Edwards, 1980).

1.10 Summary

Suitable methods to assess the force-velocity and power output characteristics of isolated muscles have been available since the early part of this century. However, techniques to measure maximal dynamic muscle function in humans during exercise are not as simple or as established as in isolated preparations.

Maximal power has been calculated during running, stairclimbing, jumping, rowing and cycling, but in all these activities the load is not suitably matched to the muscles so as to exploit to the utmost their intrinsic force-velocity characteristic. Furthermore, maximal force generated at different velocities of movement cannot be measured.

Due to such methodological problems there is a minor emphasis in research literature on the production of maximal power output during short-term exercise, compared to studies of submaximal steady-state exercise; this despite the fact that many daily activities such as stairclimbing involve brief efforts of high intensity.

The work described in this thesis had a number of objectives related to the more complete study of muscles engaged in short-term maximal exercise. The primary purpose was to develop a mechanical system based on cycling, capable of quantifying the maximal work output of the legs over as wide a range of pedalling speeds as possible.

In isolated muscle the force-velocity characteristic dictates that there are two optimum speeds, one for maximum power output (P/Po = 0.3) and one for the greatest efficiency (P/Po = 0.5) (Hill, 1956; 1964c). A secondary objective of this thesis was to determine if similar relationships could be identified in human muscles in vivo. An investigation of the torque-velocity and power-velocity behaviour of human leg muscles during maximal cycling exercise afforded the opportunity to identify the optimal pedal crank velocity for maximal mechanical power output. Measurements were also made of the power output, total work and fatigue during maximal short-term cycling exercise performed at different pedalling speeds. Thus it was possible to test the hypothesis that maximal cycling performed at fast pedalling speeds would be less efficient than at slow speeds, resulting in a concomitantly greater fatigue.

The following chapters describe the construction and testing of the system and its subsequent application to these problems.

2. GENERAL METHODS

A major goal of this thesis was to develop a cycle ergometer capable of absorbing the maximum work output of the legs, over a wide range of constant angular velocities of the pedal cranks. During the course of development many modifications were made to various parts of the ergometer, and the measurement of mechanical power progressed from simple manual calculations to continuous on-line sampling of electrical signals by a laboratory computer. This chapter will provide a description of the ergometer, an outline of the standard procedures employed in all testing and present data from the earliest study which provided a test of the instrument's reliability and versatility.

2.1 Design and Applications of the Constant-Velocity Ergometer

The constant velocity ergometer (CVE) is a modified ergometer with a strengthened steel frame (Fig. 5).

2.1.1 Speed Control

The maximal power output of human leg muscles in a single bilateral movement is approximately six to seven horsepower (Wilkie, 1960); thus a single leg might generate three horsepower. For this reason it was important that the cranks of the CVE could be maintained at a constant velocity

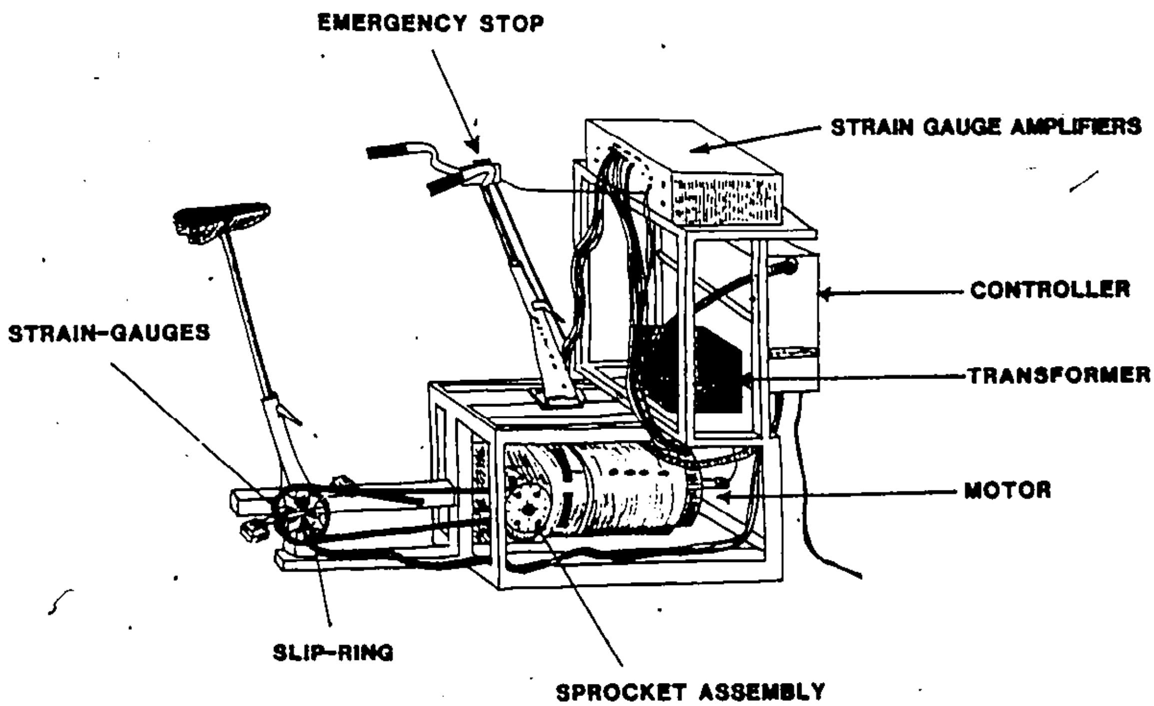


Figure 5. Diagrammatic sketch of the constant velocity ergometer.

despite subject generated forces up to three horsepower. To ensure precise speed regulation a Fincore DC regenerative speed controller (SC1154B) supplies electrical energy to a three horsepower DC electric constant torque motor (Boston Gear 18300-C), which is connected in series to a 10:1 motor reducer. A wide range of pedalling speeds is provided by a sprocket assembly containing a unidirectional clutch which is attached to the reducer drive shaft, and linked to the ergometer's chain wheel by a conventional bicycle chain. The electric motor generates three horsepower at its base speed of 1750 rpm, and may be operated as high as 2300 rpm with a concomitant 10% increase in horsepower. The speed controller responds to a DC tachometer feedback circuit (Fincore 1042564), and provides rapid speed regulation with respect to load changes by adjusting the level of power delivered to the motor. Once the motor is activated the angular velocity of the reducer drive shaft may be varied by adjusting the controller speed potentiometer; the unidirectional clutch prevents the pedal cranks from turning until the subject chooses to begin cycling. However, in case of clutch failure an emergency stop button is attached to the handlebars within easy reach of the subject and investigator. During a test the subject pedals to catch up to the preset speed of the motor and then exerts maximal force against the resistance offered by the motor load. The regenerative speed controller ensures that forces momentarily as high as three horsepower, result in speed variations of less than 5%; this leads to the same sensation as pedalling a cycle up a very steep incline.

In the early stages of development the sprocket attached to the reducer drive shaft had a complement of 18 teeth, resulting in a gearing ratio of 2.66 between the front sprocket and the chain wheel and 26.6 between the chain wheel velocity and the motor speed. Preliminary studies indicated that at pedal crank velocities less than 50 rpm the motor could be overdriven as soon as the subject applied enough force to overcome frictional losses and surpass the motor's torque capacity. At a pedal crank velocity of 50 rpm the motor speed would be (50 x 26.6) 1330 rpm, appreciably below the base rate of 1750 rpm required for the production of three horsepower. Therefore it was necessary to operate the motor at or above its base rate, to prevent a fall in horsepower. For this reason the early studies were completed at a pedal crank velocity of 60 rpm.

A major requirement of the CVE was to measure maximal force generation over a wide range of pedalling speeds. To achieve this aim a conventional racing cycle rear derailer system comprising five sprockets was mounted on the motor reducer drive shaft (Fig. 6). Sprocket size varied from 14 to 34 teeth and afforded a range of pedalling frequencies from

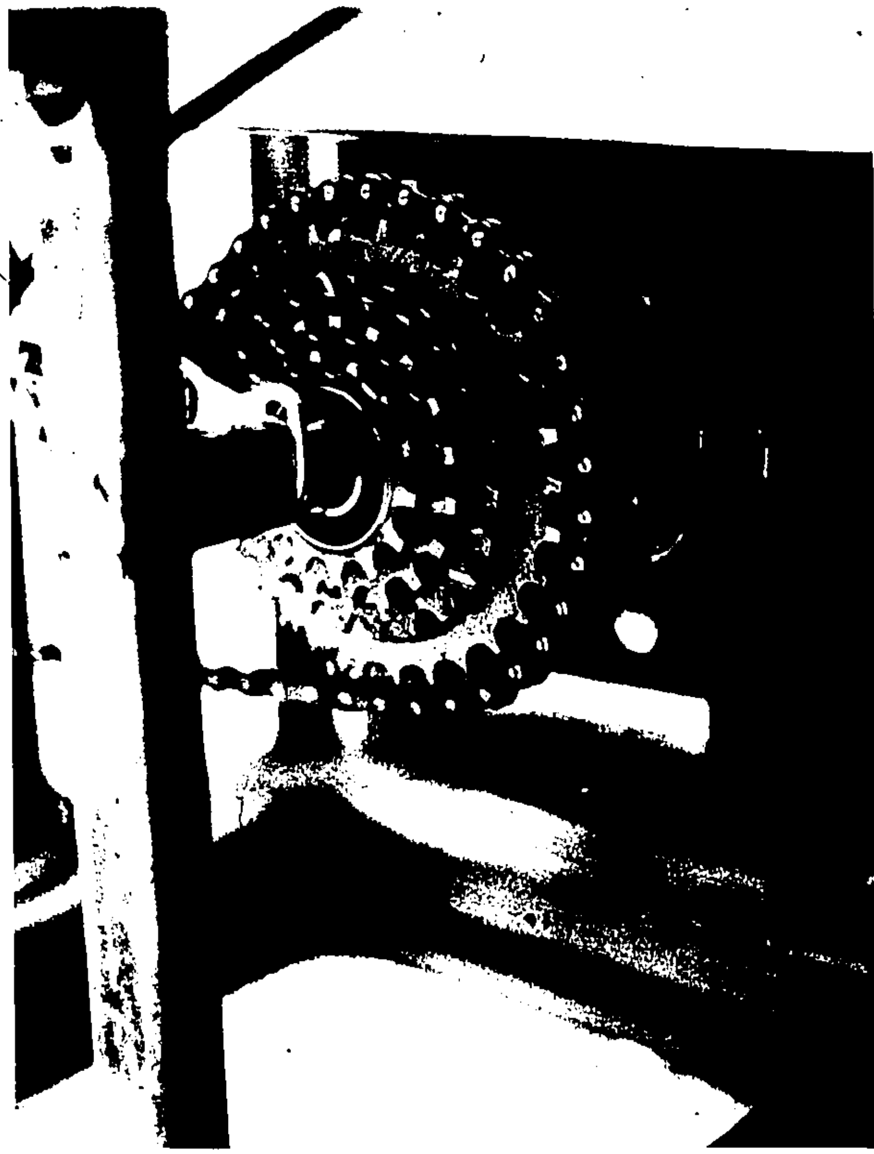


Figure 6. Five sprockets attached to the motor reducer drive-shaft which afforded a range of pedalling speeds from 13 to 166 rpm, at a motor speed of at least 1750 rpm.

13 to 166 rpm, but below 30 rpm the motor could still be overdriven by as much as 15%. Moreover, the torque generated by powerful subjects at low pedalling rates was great enough to permanently deform the pedal cranks. Due to these methodological problems it was decided to restrict testing to crank velocities greater than 50 rpm.

2.1.2 Method of Force Recording

Forces applied to the pedal cranks are detected by matched pairs of resistance strain gauges (Micro-measurements CEA-06-250VW-350) bonded to the flat surface midway along the trailing and leading edges of each crank. The gauges of each crank form two elements of self-balancing Wheatstone bridge circuits, one circuit for the left crank and the other for the right crank. Power supply to the strain gauges and the signals from the gauges are connected to amplifiers through five wiping brass slip ring contacts on each crank (Fig. 7) (Atkins and Nicholson, 1963). The output from the amplifiers is channeled to a Hewlett Packard chart recorder (7700 series), and may also be sampled on-line and stored on a floppy disc by a laboratory computer (Digital Equipment Corp.). The force trace from the recorder may be analysed graphically by planimetry or the results may be calculated directly by the computer, which samples torque at ten millisecond intervals and performs integration with respect

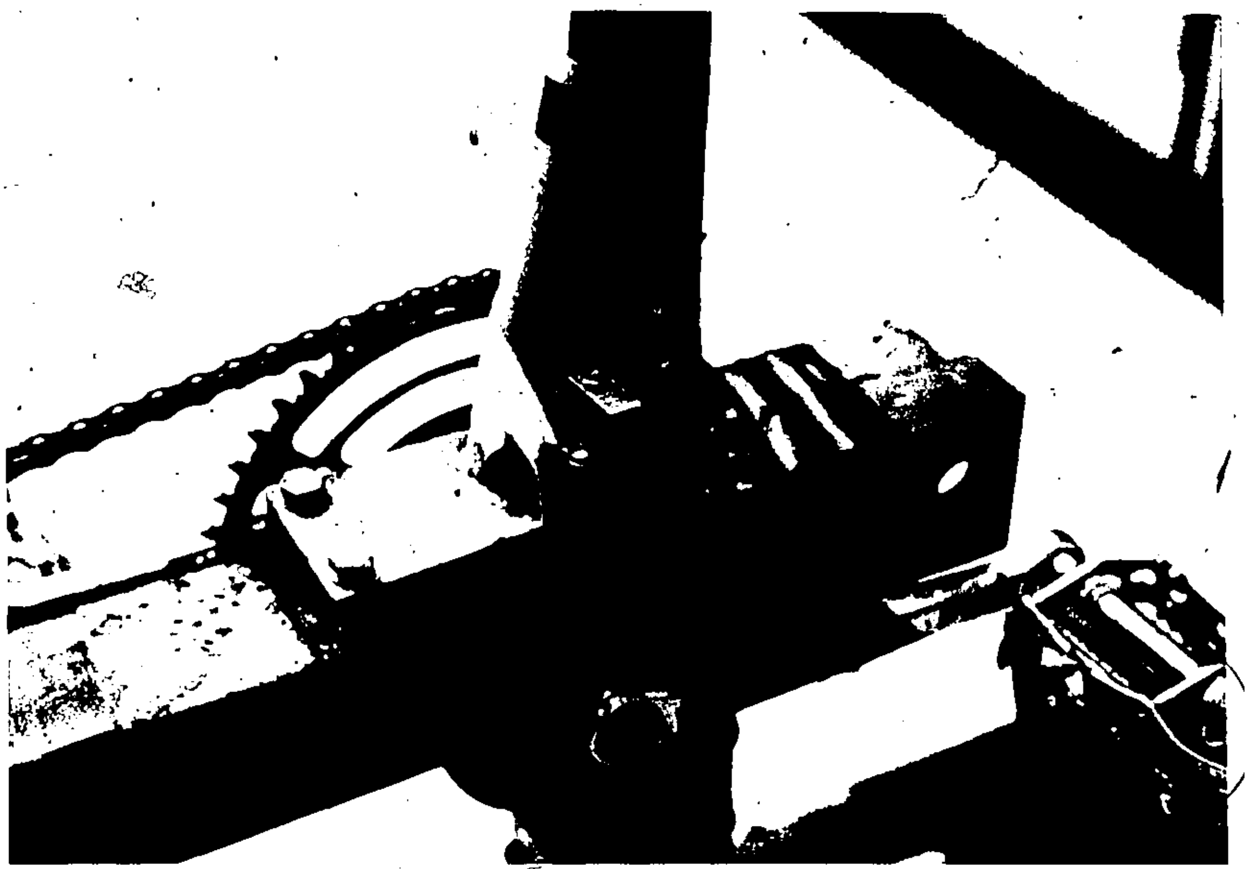


Figure 7. The wiping brass slip ring contact on each crank transmitted the signals from the resistance strain gauges to the strain gauge amplifiers. Also visible in the centre of the picture is a microswitch, activated by mechanical contact with the crank in the top-dead-centre position.

to time (Appendix 6). A magnetically operated reed switch, and a mechanically activated microswitch detect the position of each crank at various points in every revolution, thus allowing the calculation of angular velocity.

2.1.3 Calibration

Initially the system was calibrated statically by suspending weights from each pedal locked in the 90° position (Fig. 8) in 22.7 kg (222.6 N) increments, up to and including 136.1 kg (1334.7 N). Calibration was performed daily over several weeks and the responses were linear and precise throughout the range; the mean coefficient of variation for both pedals was 1.5%. Thereafter a one or two point calibration was found to be acceptable for working purposes.

2.1.4 Calculation of Torque, Work and Power

The International System of Units defines unit force as that which gives the mass of 1 kg an acceleration of $1 m \cdot s^{-2}$, and is called the newton (N). When a force acts about an axis of rotation it produces instantaneous torque equal to the product of the force multiplied by the perpendicular distance from the axis of rotation, measured in metres. Instantaneous torque exerted on the pedals of the CVE is therefore calculated as the product of the mass (M,

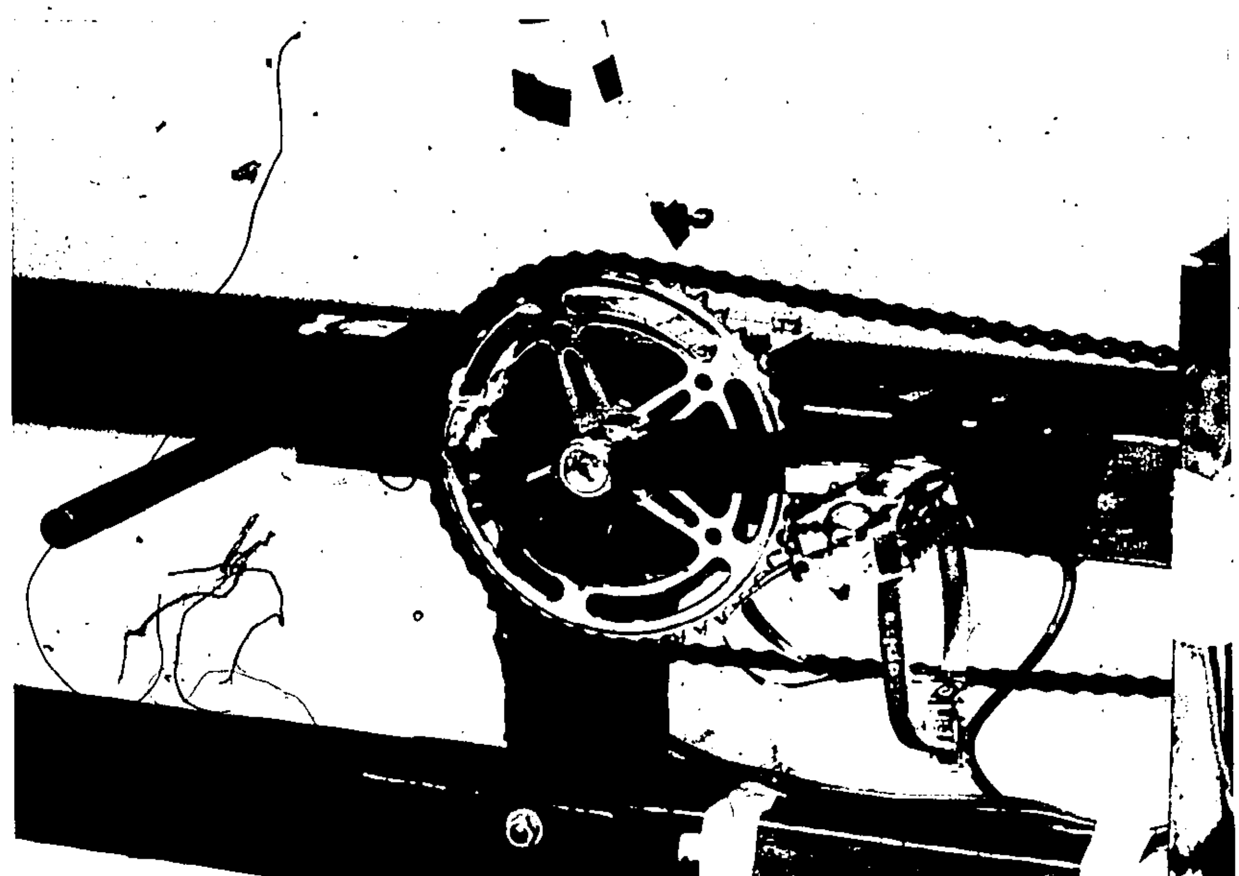


Figure 8. A locking bar enabled each pedal in turn to be calibrated statically by suspending various weights from the pedal.

kg) multiplied by the gravitational constant (9.807, $m \cdot s^{-2}$) and the length of the crank from the axis of rotation (l, m): Instantaneous torque (N·m) = M x 9.807 x l.

The unit of work is the newton metre or joule, and is achieved when a force of one newton acts through a distance of one metre. External work performed on the CVE is represented by the area under the torque-time curve (impulse) and is the product of the constant angular velocity ($rad \cdot s^{-1}$) and the integral of torque with respect to time.

Power is the rate of doing work; the unit of measurement is the $J \cdot s^{-1}$ or watt. Power output on the CVE is calculated from the work divided by the time taken for the pedal crank to rotate 360°. Instantaneous power is the rate of doing work at any instant during a cycle, and equal to the instantaneous torque (N·m) multiplied by the angular velocity of the crank ($rad \cdot s^{-1}$). It has been argued by Moffroid et al (1969) that because muscular torque varies through an arc of motion, instantaneous power is a more definitive measure of muscular performance at different velocities of movement.

In the studies included in the main body of this thesis which report measurements of work, and average power, the method of calculation was based on manual planimetry of the force record from chart paper (Fig. 9). The raw data and appropriate calibration factors were then fed into a computer, which performed the necessary calculations for each pedal cycle. During the course of development the method of force recording became more sophisticated. Eventually, the voltage output from the strain gauge amplifiers was sampled directly by the computer at ten millisecond intervals (Appendix 6). Several comparisons were made of the values obtained by planimetry and by computer, and the agreement between the two methods was very close. The coefficient of variation for paired values of instantaneous peak power and average power was less than 2 and 6%, respectively.

2.1.5 Pattern of Force Application During a Cycle

There have been several investigations of the pattern of force application during normal cycling (Atkins and Nicholson, 1963; Hoes et al, 1968; Soden and Adeyefa, 1979) and the results in this thesis concur with previous findings.

In figure 10 the distance between microswitch pulses represents a 360° turn of the pedal cranks from when the right crank is at top dead centre. It can be seen that the majority of work performed in a complete revolution actually occurs during the first 180° of rotation, from top dead centre to bottom dead centre. Peak instanteous torque (A) is generated consistently when the pedal crank is in the forward

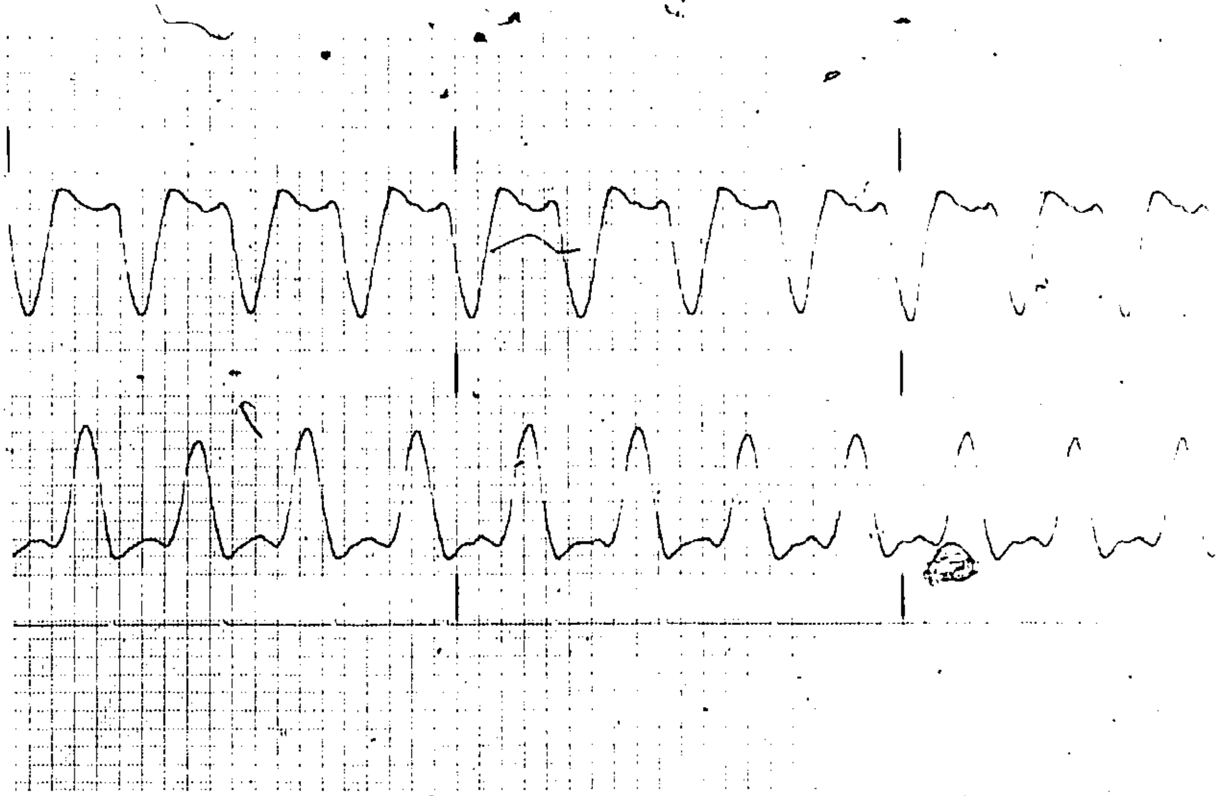


Figure 9. An example of the force trace recorded on chart paper. The right leg is represented by the top series of curves. Each curve depicts the amount of force generated by a single leg in one pedal cycle.

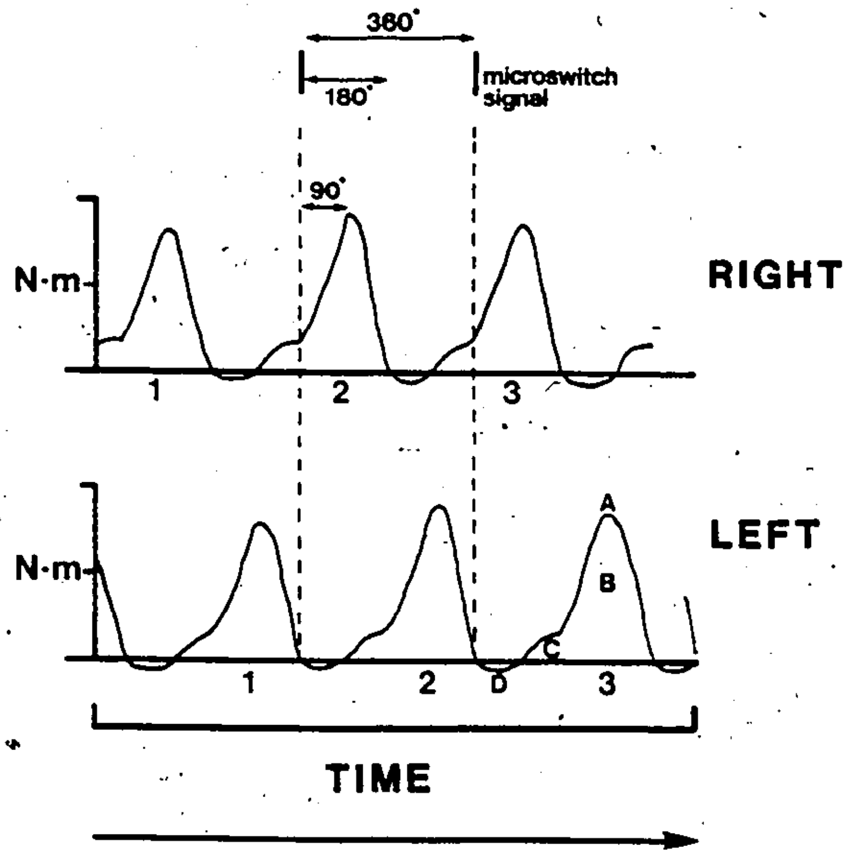


Figure 10. The pattern of force application displayed by each leg during three pedal cycles. For explanation refer to text.

horizontal position, and the mechanical advantage to the subject is most favourable.

In figure 10 the deflection C corresponds to a pull-up phase immediately prior to the pedal position reaching top dead centre. The degree of pull-up varies between subjects and tends to disappear at high crank velocities. The negative deflection D represents the passive weight of the leg on the pedal at the beginning of recovery; removing the foot from the pedal during this phase causes the negative deflection to disappear (Hoes et al, 1968). Torque records obtained during preliminary testing revealed considerable variability in both the presence, and the extent of negative deflections below the baseline. For this reason, and because the passive negative force contributed by one leg must be opposed simultaneously by an equal positive force generated by the other leg only the positive forces registered above the baseline were included in the analysis.

2.1.6 Standard Testing Procedures

Certain standard procedures were developed and followed in all testing. The optimal saddle height was selected for each subject corresponding to a position which allowed slight knee flexion when the pedal crank was angled vertically downwards. The same saddle height was used for each subject in every test. Toe clips and straps attached the feet to the pedals and a restraining harness around the hips served to limit the exercise to the lower limbs without restricting movement (Fig. 11). Warming-up procedures were not used; subjects rested in the temperature controlled laboratory for fifteen minutes before the test. When the motor was activated the subject was allowed a brief time (2 - 3 s) to catch up to the speed setting before exerting maximal force on the pedals.

In every study reported in this thesis the procedures involved in the testing, including possible risks, were explained to the subjects and informed consent was obtained (Appendix 5). All studies were approved by the university ethics committee.

2.2 Intra-Individual Variation and Repeatability of Measurements

The standard procedures outlined in the preceding section were followed in the earliest study, which was completed at a time when the CVE was equipped with a single 18 tooth sprocket on the motor reducer drive shaft. The purpose of the investigation was to examine intra and inter-individual differences in peak torque production throughout a maximal 45 second test on the CVE at 60 rpm (complete results in Appendix 7). Before proceeding with further modifications to the ergometer it was thought

Figure 11. Standard procedures were employed in all testing. Toe clips and straps attached the feet to the pedals and a restraining harness around the hips limited the exercise to the lower limbs without restricting movement.

important to establish the normal variability in performance between legs, and the repeatability of measurements in a given individual at this one speed.

Seventeen healthy male subjects (Appendix 7) participated in the study; the torque output was recorded on chart paper and peak torque was calculated for each leg separately during every revolution, in addition to a mean value for both legs. The decrease in torque by the end of the test was expressed as the percentage decline from the highest peak values ($\bar{x}$ of 5 successive pedal cycles), and used as an index of fatique (FI). Seven subjects performed a repeat test on another occasion to examine the day-to-day variability in performance. Differences in the peak torque and the FI between legs were compared using Student's t-test; the repeat values were compared using Student's t-test for matched pairs (2-tailed test) and a coefficient of variation was calculated (CV = $\frac{\text{SD diff}}{(\bar{x}_1 + \bar{x}_2)/2}$ in which SD diff = the standard deviation of the mean difference between double values).

A variable pattern of dominance was found between legs but in the group as a whole the right leg proved to be slightly more powerful throughout the test (Fig. 12); the differences in maximal peak torque and the FI were small, and not significant. In most subjects the difference in peak torque production between legs was less than 10% at the

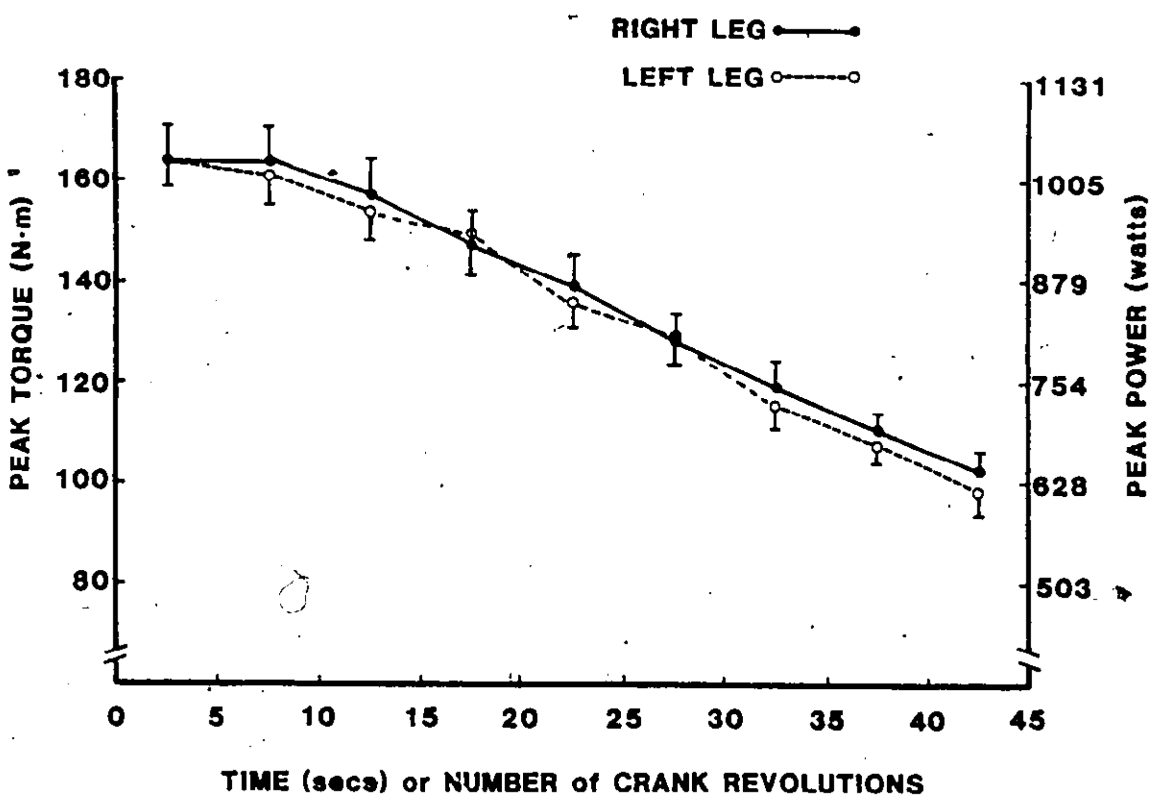


Figure 12. Measurements obtained in 17 subjects of peak torque and power produced by each leg during 45 s of maximal cycling at 60 rpm. Values are the mean ±1 S.E.M. of five consecutive pedal cycles.

beginning of the test, but occasionally increased to greater than 15% after 45 seconds of maximal effort. If one leg was dominant in the early stage of the test it usually maintained a consistent dominance throughout. When there was a marked variation between legs the CVE proved that it was sensitive enough to quantify the differences. This is shown clearly in figure 13 which depicts weakness of the right leg in a healthy male aged 25, caused by residual post-traumatic atrophy in the vastus group of muscles.

The repeatability of the test was examined in seven subjects, selected at random. A paired t-test indicated no significant differences in either the maximal peak torque or the FI between the two tests (Fig. 14); the coefficient of variation was 6.5 and 16.5% respectively.

These initial studies confirmed that the CVE was a sensitive, reliable instrument for quantifying the maximal torque generation and fatigue characteristics of human leg muscles, during short-term dynamic exercise performed at a crank velocity of 60 rpm. The device was capable of recording both intra and inter-individual differences, and the measurements of torque and fatigue were reproducible in a given individual. Subsequently, the CVE was modified as previously described to permit testing over a very wide range of pedalling speeds.

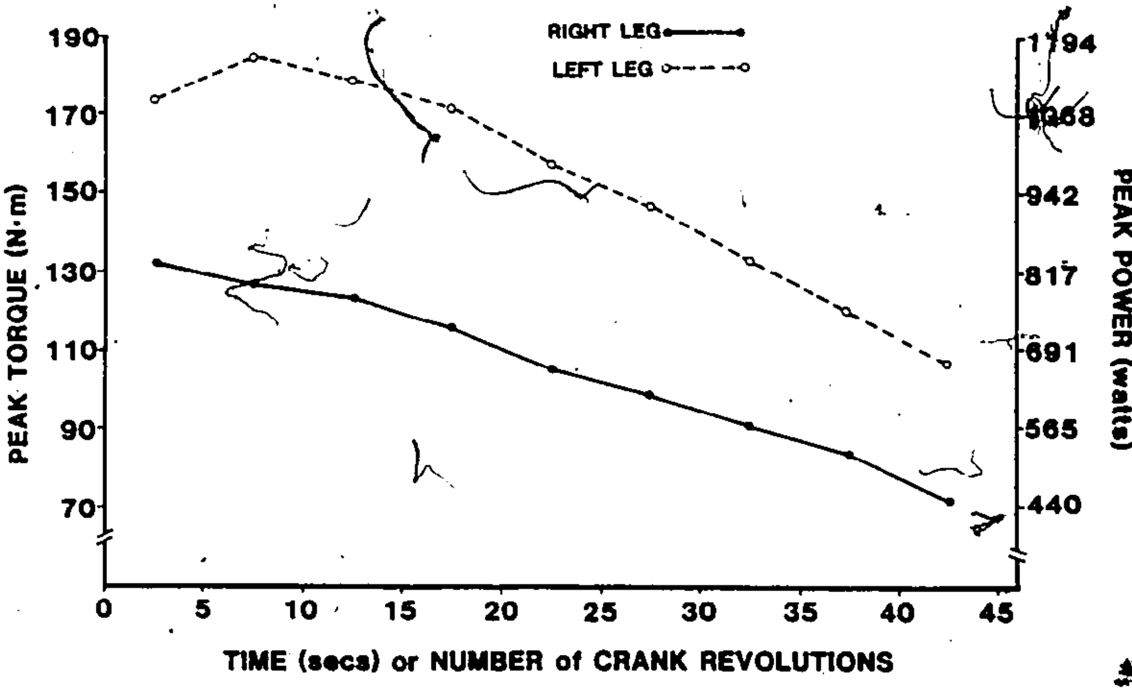


Figure 13. Differences between legs in peak torque developed by a subject with post traumatic atrophy of the right vastus group. Values are the mean of five consecutive pedal cycles.

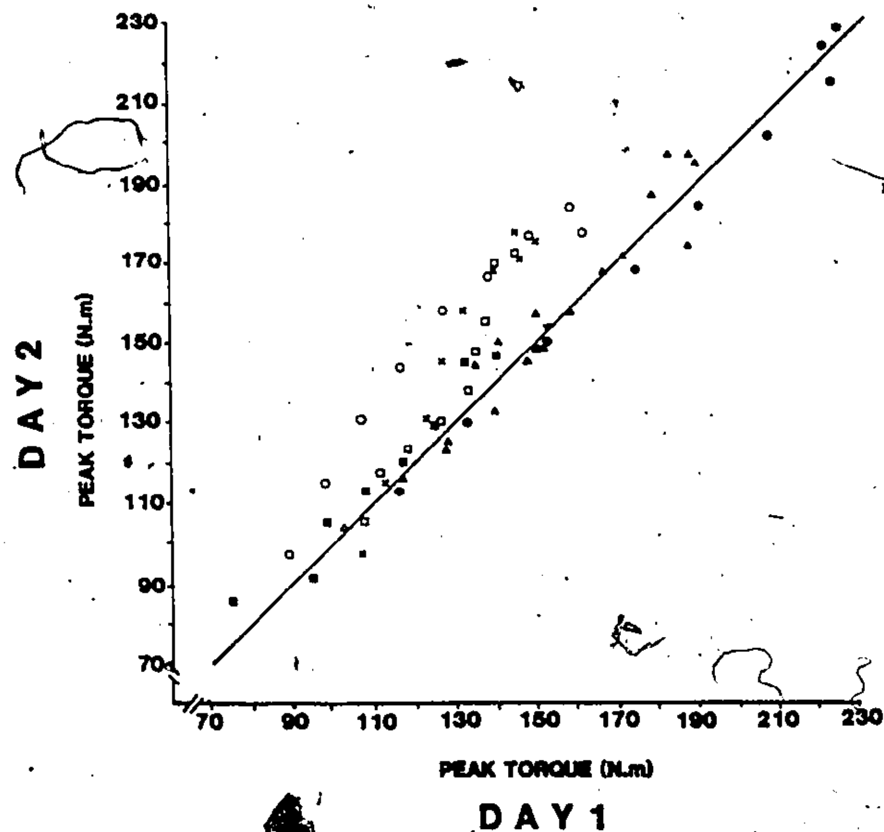


Figure 14. Measurements obtained in seven subjects of peak torque (mean of both legs) generated throughout 45 s at a crank velocity of 60 rpm on two occasions, 24 hours apart. Data points represent the mean of five consecutive pedal cycles. The line shown is the line of identity. Although the peak torque tended to be higher on the second day, there were no significant differences in either the maximal peak torque or the fatigue index.

In the rest of the studies reported in this thesis similar techniques were employed to assess intra-individual differences and the repeatability of measurements in a given individual, at a variety of pedalling speeds and during tests of varying duration. In general, the right leg exhibited a degree of dominance which often became more pronounced during fatigue, especially at high pedalling frequencies; no significant differences between repeat tests were ever detected.

3. TORQUE-VELOCITY AND POWER-VELOCITY RELATIONSHIPS DURING MAXIMAL CYCLING EXERCISE

3.1 Introduction

The maximum velocity of shortening under a series of different isotonic loads describes a fundamental property of isolated skeletal muscle, its intrinsic force-velocity relationship. First investigated by Fenn and Marsh (1935) the force-velocity relationship was later shown mathematically by A. V. Hill (1938) to form part of a rectangular hyperbola: $(P + a)(V + b) = (Po + a)b$. Hill's characteristic equation has since been applied successfully to isolated amphibian and mammalian muscle, including human, (discussed in section 1.4) but there has not been general agreement concerning the nature of the force-velocity relationship in human muscles in vivo. Part of the uncertainty may have been caused by methodological differences which resulted in the comparison of linear and angular forces, or restricted testing to a limited portion of the overall physiological range. The work described in this section was intended to overcome some of these difficulties, and contribute to a more complete understanding of the nature of the force velocity relationship in human muscles in vivo.

3.2 Methods

3.2.1 Subjects

Twelve healthy university students ranging in age from 19 to 23 years participated in the studies. None of the subjects were highly trained but most engaged in regular recreational physical activity. Complete descriptive details of the subjects are listed in Appendix 7.

3.2.2 Experimental Protocol

The study design required that each subject complete two exercise tests. The purpose of the first test was to measure the maximal mechanical power output and cardiorespiratory responses during a progressive multistage exercise test on a cycle ergometer. This was a routine clinical test (Jones and Campbell, 1981) which is used extensively to identify individuals who may be at risk to participate in very strenuous exercise. Subjects were to return to the laboratory on another two days and perform brief maximal bouts of cycling on the CVE at crank velocities of 20, 40, 60, 80, 100, 120, 140 and 160 rpm on each occasion. To standardize the peak torque data for variation in active muscle mass, the volume of thigh components between the gluteal fold and knee-joint space was determined in each subject by an physical anthropometric technique (Jones and

Pearson, 1969), and computerizd tomography (Hounsfield, 1973) respectively (Appendix 2).

3.2.3 Progressive Multistage Exercise Test

The progressive multistage exercise test was performed on a calibrated electrically braked cycle ergometer (Elema, model EM370). The initial power output was set at 100 kpm/min (~17W) and increasd by 100 kpm/min at the end of each minute, until the subject could not continue. The subject breathed through a low resistance, low deadspace valve, and inspired ventilation was measured by a dry gas meter (Parkinson-Cowan CD4). Expired gas was passed through a mixing chamber and analysed for oxygen and carbon dioxide by calibrated O_2 (Godart Rapox) and CO_2 (Godart Capnograph) analysers. Analog data displayed on an 8 channel recorder (Mingograf 81, Siemens-Elema) were used to calculate maximal oxygen uptake ($\dot{V}O_2$ max). Heart rate was calculated from the electrocardiogram recorded on chart paper.

3.2.4. Torque-Velocity Test

Many of the procedures outlined in section 2.1.6 of the previous chapter were employed in the study of torque-velocity relationships. The sequence of crank velocities was selected at random, and the testing protocol was standardized. The subject was allowed 2-3 s to catch up to the angular velocity of the motor and then instructed to exert maximal force on the pedals. When the force records reached a peak and then showed a consistent pattern of decline the test was terminated, usually after 5-10 s. The subject then rested for two minutes before repeating the test at another crank velocity.. This procedure was followed until the subject had completed tests at each of the crank velocities, and the entire protocol was repeated on another day to study the variability of measurements within a given subject.

It was intended that all twelve sujects would complete bouts of cycling at eight crank velocities, ranging from 20 to 160 rpm. However, this did not in fact take place. During testing of a particularly strong subject at 20 rpm the baseline of the force trace displayed on the chart recorder began to wander upwards. It was not possible to reset the strain gauge amplifiers to zero voltage, and inspection of the pedal cranks revealed that they were markedly bent, resulting in a 5 volt offset in the electrical signal from the strain gauges. Consequently the pedal assembly was replaced, and future testing was restricted to crank velocities greater than 50 rpm.

3.2.5 Calculation of Torque and Power

The force data recorded on chart paper were analysed manually. Peak torque was calculated for each leg separately during every pedal revolution, in addition to a mean value for both legs; peak power was calculated from peak torque and crank velocity, and the maximal values obtained on day 1 and day 2 were averaged. The values of peak torque and power were also standardized for each individual's thigh muscle plus bone volume determined by physical anthropometry, and muscle volume determined by computerized tomography (Appendix 2).

3.2.6 Statistics

The relation between maximal peak torque and pedal crank velocity was examined by calculation of the linear regression equation and the correlation coefficient; the values for slope and intercept of the relationship obtained on day 1 were compared with those obtained on day 2 using Student's t-test for matched pairs (2-tailed test). In addition, a coefficient of variation was computed for the 12 paired values of slope, and intercept. The association between maximal peak torque production and thigh muscle volume was assessed both across, and within crank velocities, by an analysis of covariance, and Pearson correlation analysis, respectively.

3.3 Results

3.3.1 Torque-Velocity Relationships

At each pedalling speed, peak torque was generated at the forward horizontal (90°) position of the crank, thus measurements were obtained at an equivalent muscle length in a given subject.

In the twelve subjects who performed tests at six pedalling speeds maximal peak torque was inversely and linearly related to crank velocity ($r = -0.99$). Figure 15 displays the relationship, calculated as an average of the mean values of both legs obtained on two separate days (complete results in Appendix 7). The relationship between maximal peak torque and pedal crank velocity was linear in all subjects, but there was a wide variation in the values for the slope and intercept. Figure 16 is representative of the variation in the group of subjects studied.

Intra-individual differences in maximal peak torque production between legs were very small (Fig. 17) and not significant, thus it was considered appropriate to present the data as representing a mean value of both legs. The reproducibility of the test in a given individual was very high (Fig. 18); there was no significant difference between repeat values for either the slope or intercept of the relationship ($p > 0.1$). The coefficient of variation for the 12 paired

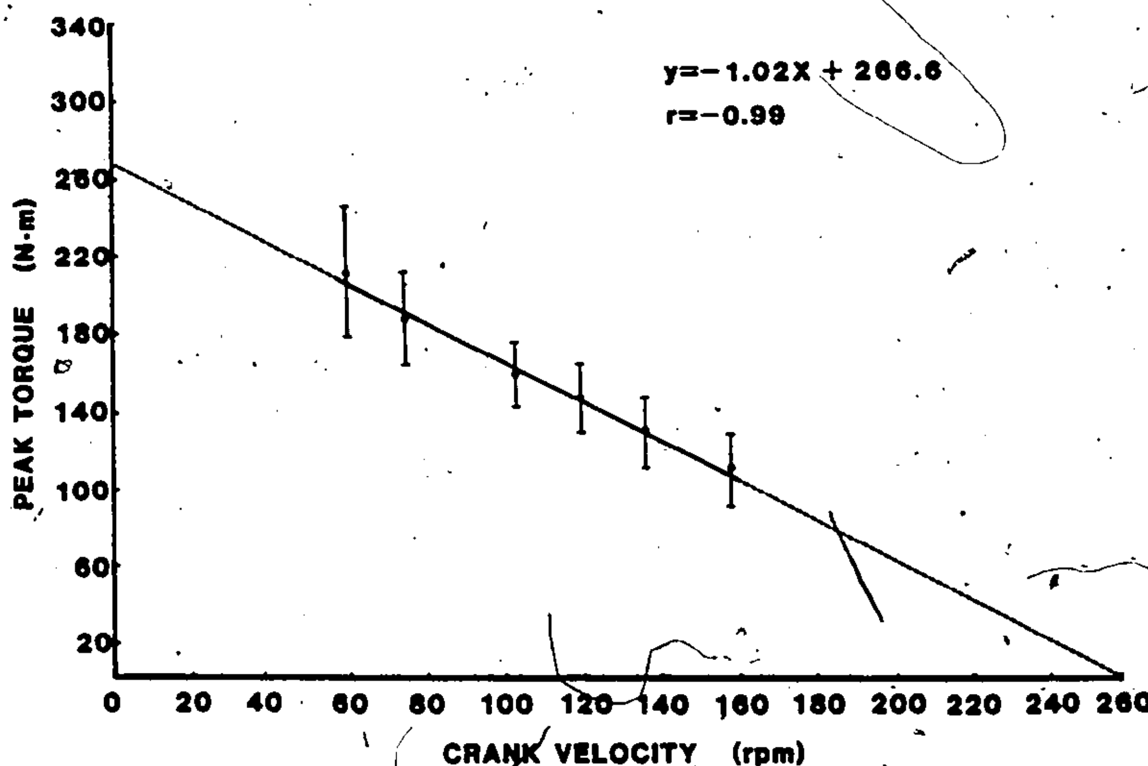


Figure 15. Measurements obtained in 12 subjects of maximal peak torque (mean ±1 S.D.) at six pedal crank velocities. The relationship was calculated as an average of the mean values for both legs recorded on two separate days.

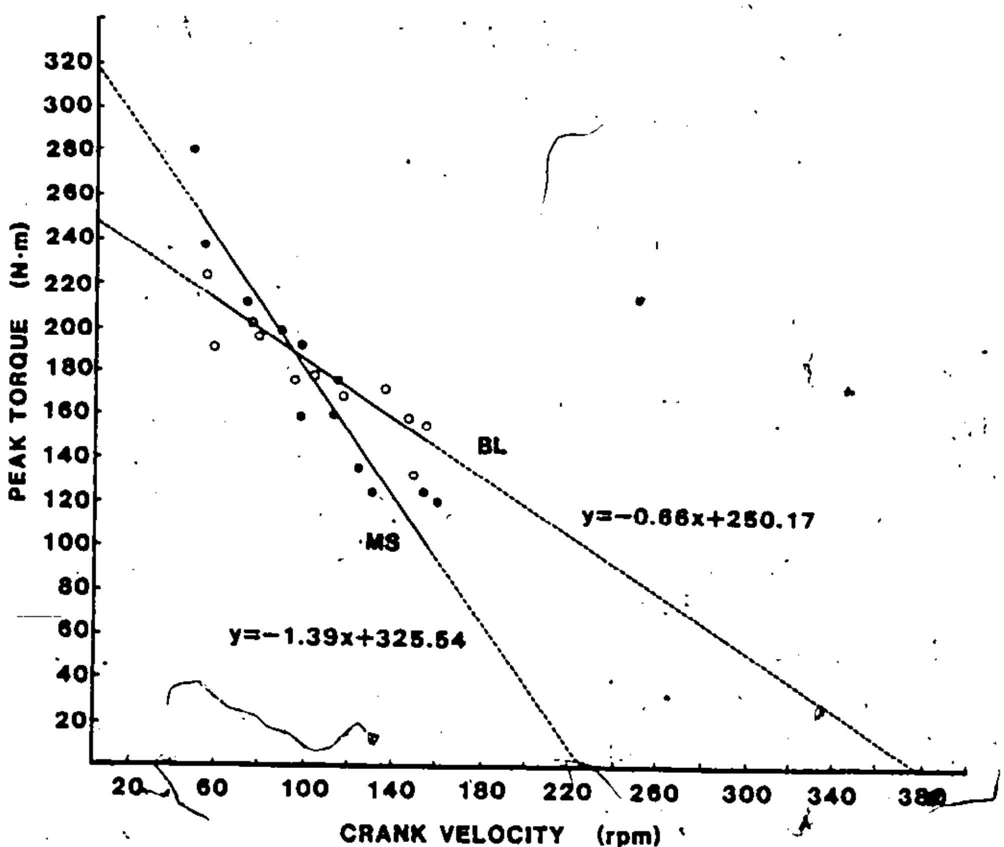


Figure 16. Relationship between maximal peak torque and pedal crank velocity in two subjects representative of the widest range of torque generation. Data points for each subject represent values obtained on two separate days.

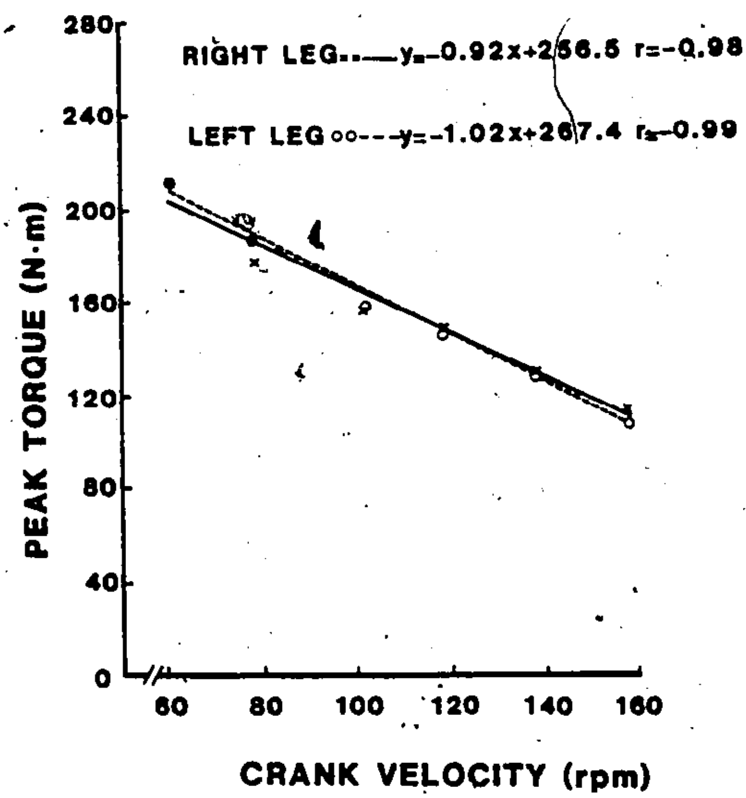


Figure 17. Measurements obtained in 12 subjects of maximal peak torque generated by each leg at six pedal crank velocities. Error bars are omitted for the sake of clarity.

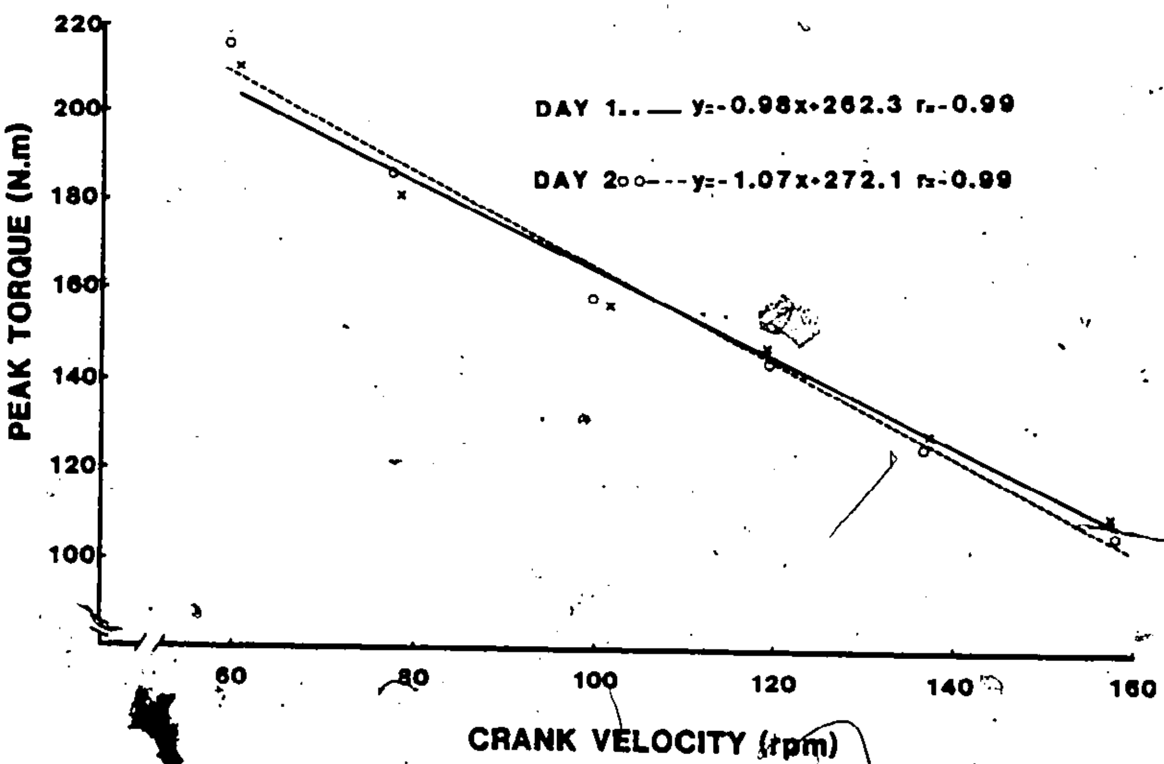


Figure 18. Measurements obtained in 12 subjects of maximal peak torque (mean of both legs) at six pedal crank velocities on two occasions, at least 24 hours apart. Error bars are omitted for the sake of clarity.

values for slope and Y intercept was 13.7 and 10.5% respectively.

Eight subjects completed tests which included two additional crank velocities, 20 and 40 rpm. The torque-crank velocity relationship remained linear (Fig. 19) and did not become curvilinear at the slower speeds. The equation of the line was similar to the previous one, describing the results of twelve subjects pedalling at six crank velocities.

3.3.2 Effects of Thigh Muscle Volume

Although peak torque values were most strongly influenced by variations in crank velocity, the volume of thigh muscle, and muscle plus bone, determined by computerized tomography and physical anthropometry respectively, was positively related to force output ($p = 0.023$). The standardized torque-velocity relationship was also linear (Fig. 20), but adjusting the data for thigh muscle, or muscle plus bone volume did not reduce the overall variability in performance.

3.3.3 Power-Velocity Relationships

Maximal peak instantaneous power output was a parabolic function of crank velocity (Fig. 21). Mean (±SD) values for maximal peak power ranged from 1323±198 and 1826±287 W, at 60 and 140 rpm respectively, corresponding to 303±49 and 425±66 $W.l^{-1}$ thigh muscle volume. There was

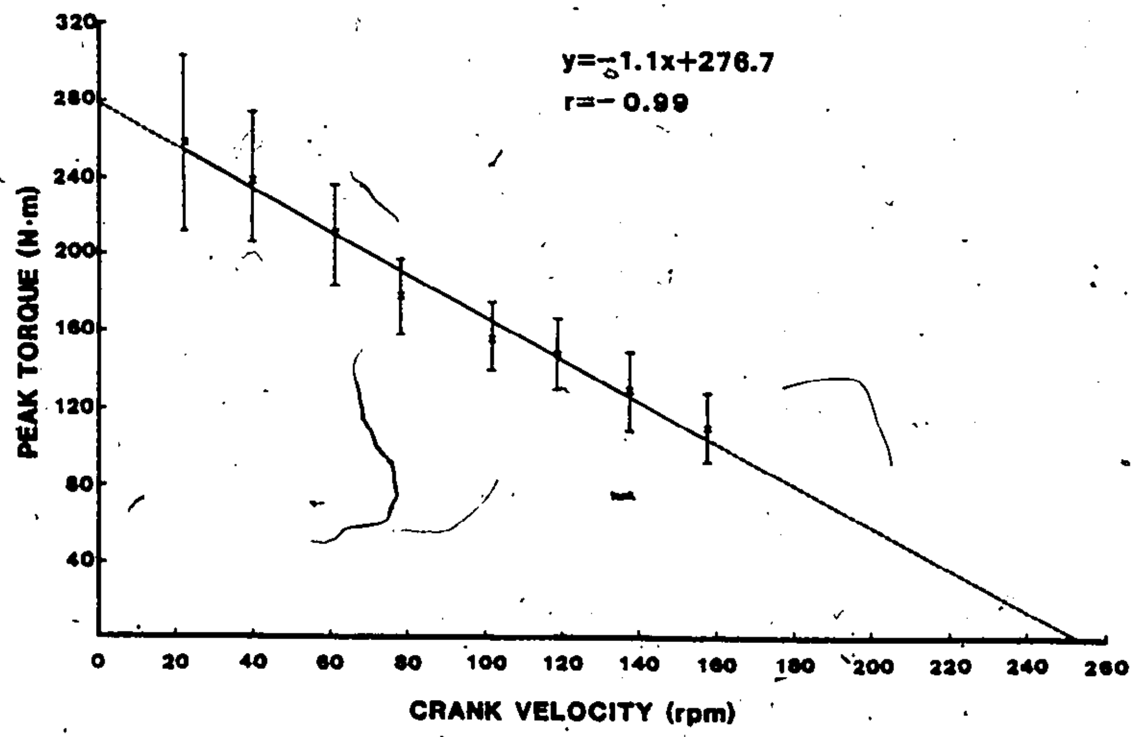


Figure 19. Measurements obtained in 8 subjects of maximal peak torque (mean ±1 S.D.) at eight pedal crank velocities. The relationship was calculated from the mean values of both legs recorded on a single day.

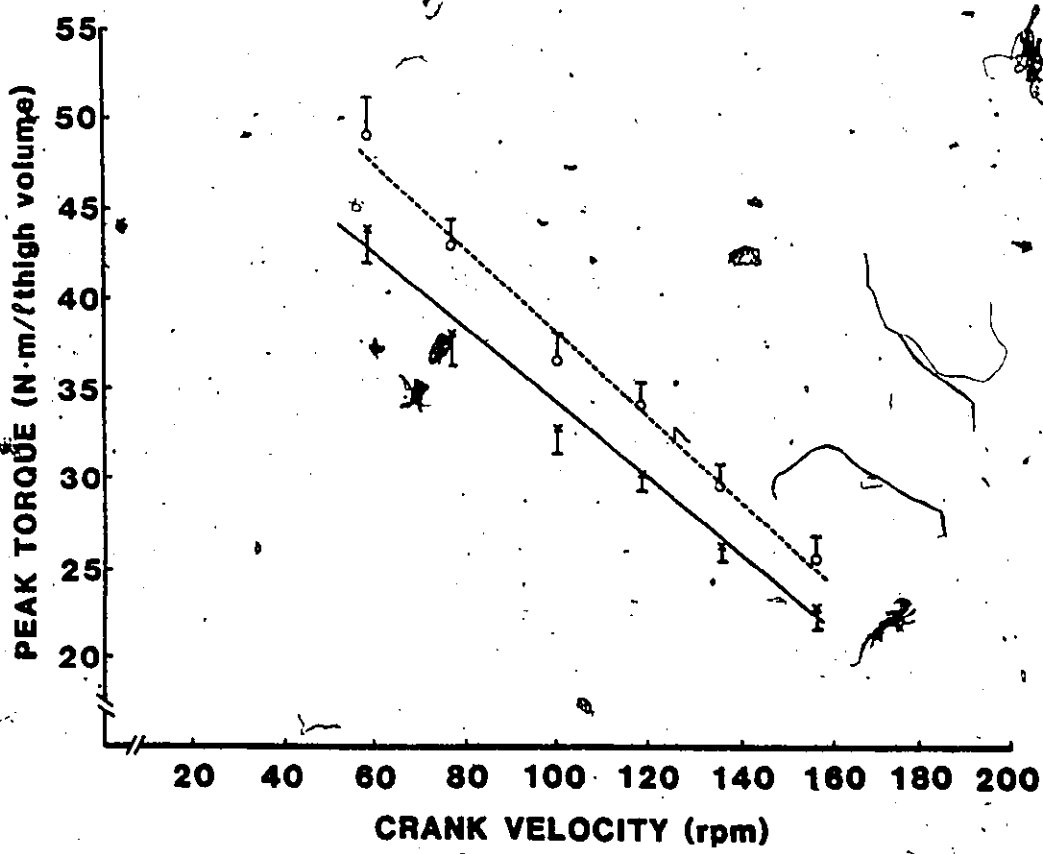


Figure 20. Measurements obtained in 12 subjects of maximal peak torque (mean ± 1 S.E.M.) at six pedal crank velocities adjusted for thigh muscle oo---- and muscle plus bone volume xx——.

no consistent crank velocity for maximal peak power output, five subjects generated their maximal power at approximately 120 rpm, four at 140 rpm and three at 160 rpm (Fig. 22 and Appendix 7). In the group of subjects who generated maximal peak power at the fastest crank velocity the mean thigh muscle volumes were slightly larger than in the group who achieved maximal peak power at 140 rpm, and larger again than the subjects who performed best at 120 rpm. However the differences were small (4.36, 4.32 and 4.21 litres) and did not reduce the variability in power output capacity. Maximal peak power output varied from (±SD) 410.6±54.5 to 506.3±54.7 $W \cdot l^{-1}$ thigh muscle volume in the subjects who performed best at 120 and 160 rpm respectively (Fig. 23). Figure 24 displays results from the same two subjects who were representative of the wide variation in slope of the torque-velocity relationship (Fig. 16). There was little difference between them in the ability to produce mechanical power at slow crank velocities. However, at pedalling rates above 80 rpm the difference became increasingly pronounced.

3.4 Discussion

3.4.1 Introduction

The work presented in this chapter was designed to provide more complete information on the nature of muscles'

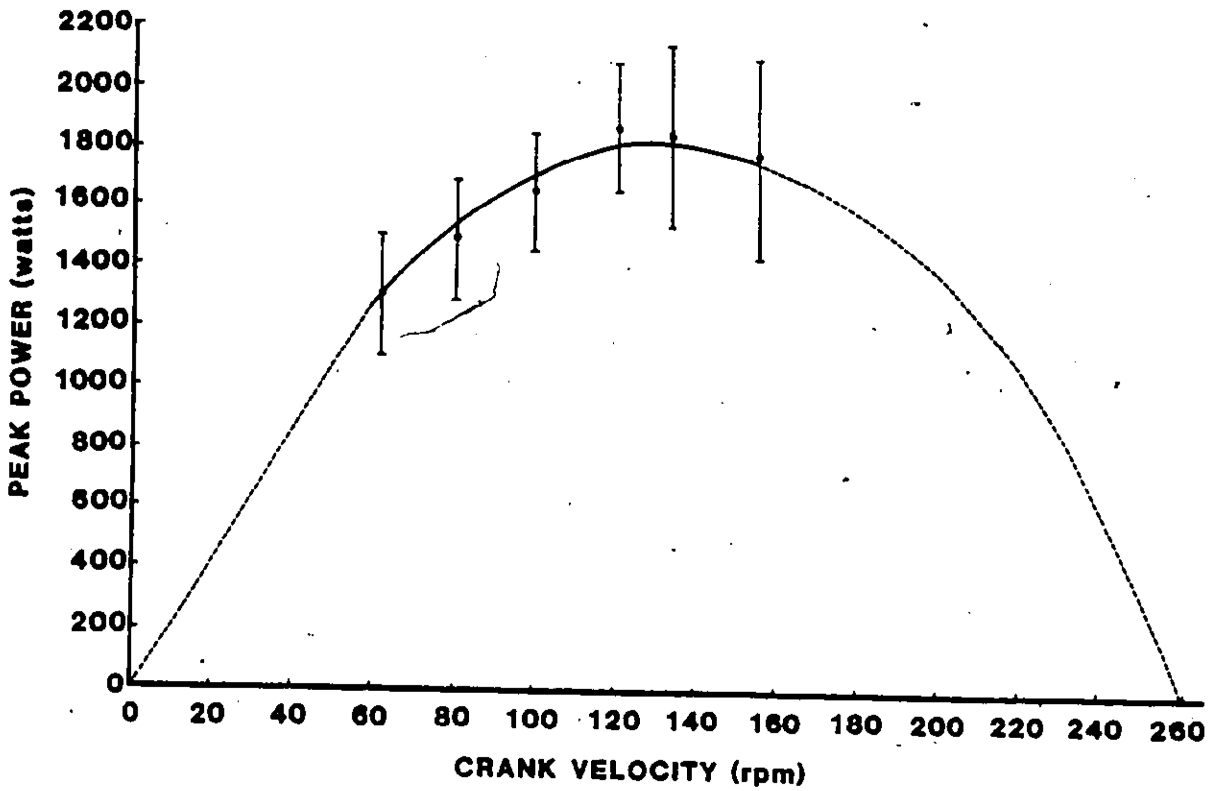


Figure 21. Measurements obtained in 12 subjects of maximal peak power (mean ±1 S.D.) at six pedal crank velocities. The relationship was calculated as an average of the mean values for both legs recorded on two separate days. These data are derived from data presented in Fig. 15 which allowed extrapolation (-----) outside the experimental range.

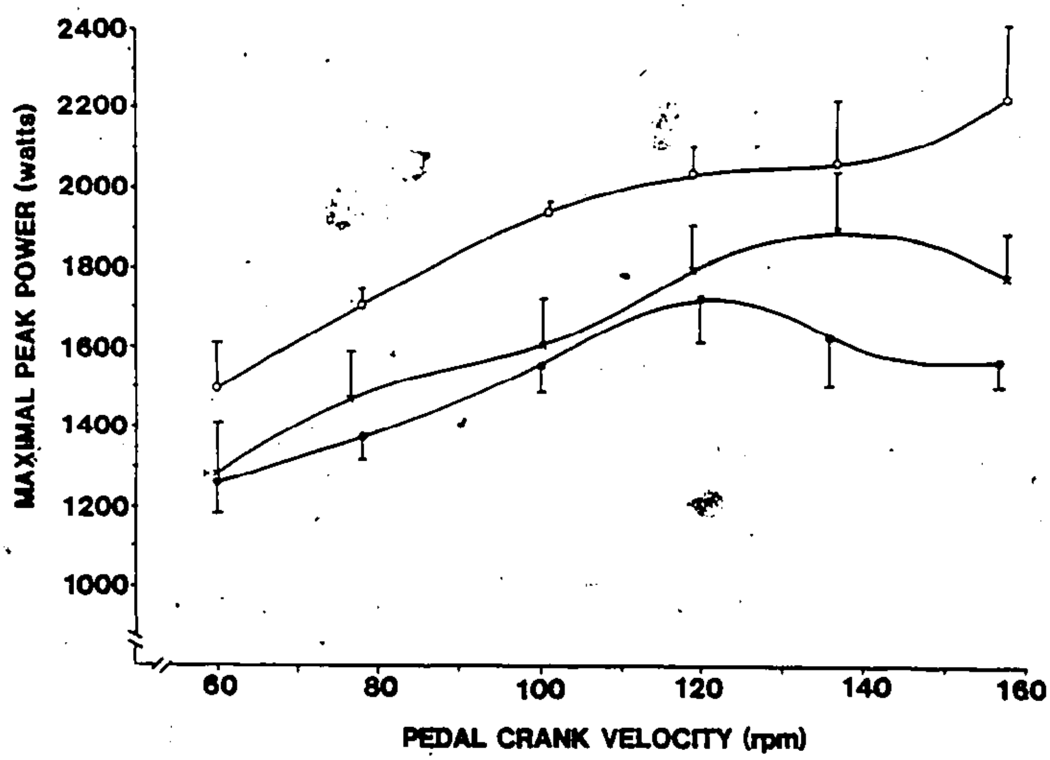


Figure 22. Maximal peak power (mean ±1 S.E.M.) at six pedal crank velocities in three groups of subjects who achieved their highest level of power at 120 ●———● (n = 5), 140 x———x (n = 4) and 160 rpm o———o (n = 3) respectively.

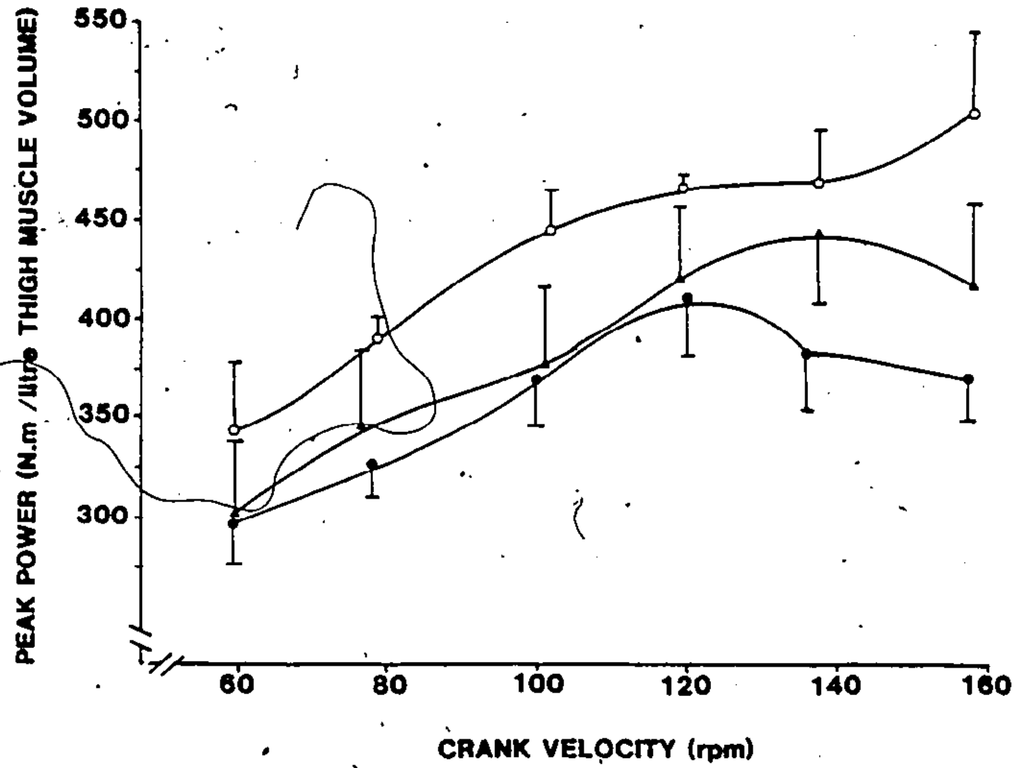


Figure 23. Maximal peak power output (adjusted for CAT thigh muscle volume) at six pedal crank velocities in three groups of subjects who achieved their highest level of power at 120 ●——● (n = 5), 140 ▲——▲ (n = 4) and 160 rpm o——o (n = 3) respectively. Data are presented as mean values ±1 S.E.M.

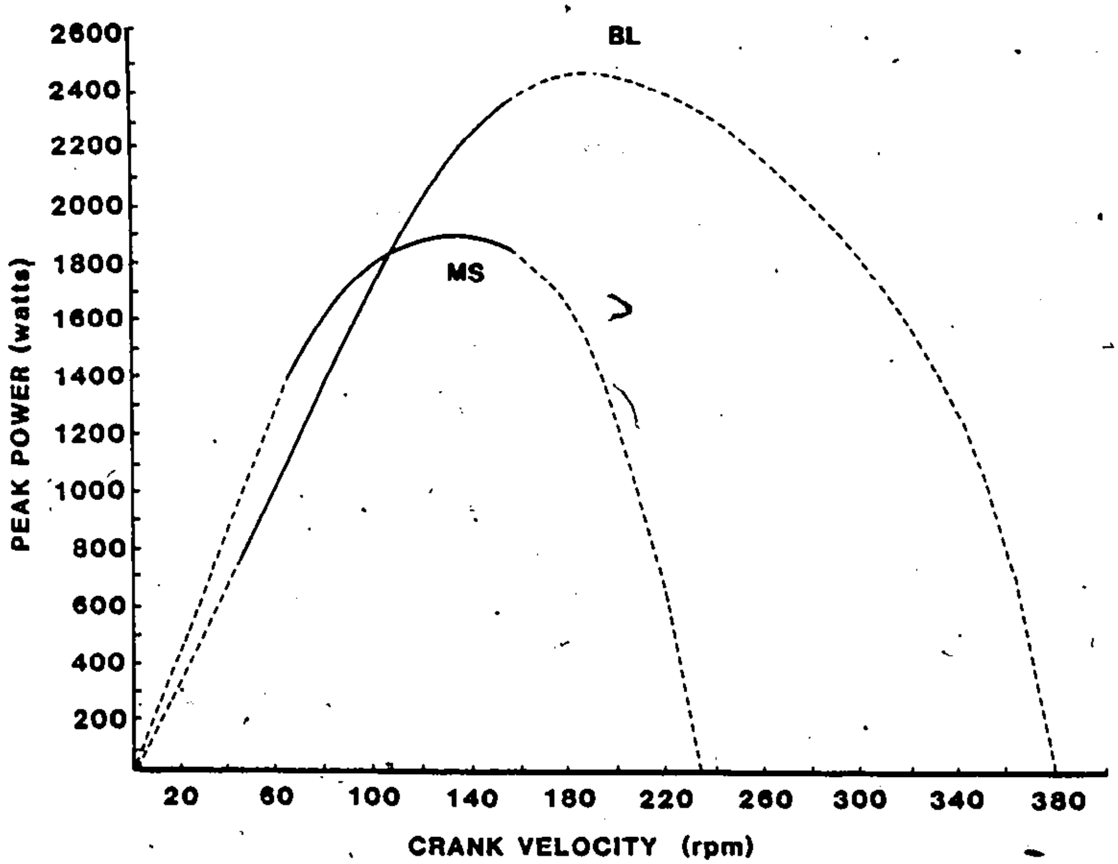


Figure 24. Maximal peak power output (mean of both legs) at 6 pedal crank velocities in the same two subjects who were representative of the wide variation in slope of the torque-velocity relationship (depicted in figure 16).

force-velocity relationship in vivo. The maximal peak torque generated by human leg muscles was measured at eight crank velocities on the CVE, over the range of 20 to 166 rpm.

3.4.2 Experimental Procedures

In classical studies of the force-velocity relationship in isolated muscles velocity (v = ds/dt; s = distance) was measured at the beginning of shortening, when there was no detectable acceleration (a = dv/dt; v = velocity) or deceleration. Since there was a constant velocity the tension in the muscle was therefore equal to the load. This is not the case in normal human movements however, which involve a constant mass accelerated, and concomitant variations in muscle tension. Early work on the force-velocity behaviour of human muscles in vivo suffered from this drawback (Wilkie, 1950). Recent investigations have measured maximal external force under conditions of imposed constant velocity (Thorstensson, Grimby and Karlsson, 1976; Perrine and Edgerton, 1978; Gregor et al, 1979) but testing has been restricted to a limited portion of the physiological range. The data in this thesis were also obtained during movements performed at constant velocity (methods described in Chapter 2), but in contrast to previous studies measurements were made over approximately 81% of the functional range (Wilkie, 1960). Unfortunately the mechanical system was unsuitable for recording maximal isometric tension (Po) and maximal voluntary velocity (Vo).

Since the first systematic investigation of the force-velocity relation in isolated frog muscle (Fenn and Marsh, 1935) it has been customary to express force in relation to either the greatest cross-sectional area or absolute mass of active muscle. In studies of human muscle in vivo an estimate of muscle plus bone size has been determined by an physical anthropometric technique (Jones and Pearson, 1969), and ultrasonic measurements (Ikai and Fukunaga, 1968; Young et al, 1980). More recently, computerized axial tomography has provided a measure of the individual contributions of fat, muscle and bone to overall limb cross- sectional area (Bulcke et al, 1979; Haagmark, Jansson and Svane, 1978; Brenton et al, 1981.)

In this thesis the volume of muscle plus bone between the gluteal fold and knee joint space was determined in each subject by the anthropometric method of Jones and Pearson (1969). In addition the volume of fat, bone, and muscle respectively, was determined between the same anatomical sites by computerized axial tomography (CAT) (Methods in Appendix 2). The first technique has been used widely in studies which required an estimate of lower limb segment volume (Davies and Sargeant, 1975; Sargeant, Hoinville and Young, 1981), whereas it was felt that CAT would provide an even more discriminating measure. The section of leg between the gluteal fold and knee joint space was selected arbitrarily as being most likely to incorporate the greatest mass of muscle activated during bicycling movements.

3.4.3 Torque-Velocity Relationships

The most striking feature of the torque-velocity data presented in this thesis is the linearity of the relationship in every subject (Fig. 15; 19). Even in the individuals who performed tests over the widest range of pedalling speeds (20-166 rpm) there was no indication of a hyperbolic curvature. Failure to demonstrate a curvilinear response may have been due to methodological constraints which prevented testing at the extremes of force and velocity. However, measurements of maximal torque were made over approximately 81% of the functional range of crank velocities (Wilkie, 1960), and it is reasonable to assume that any trend away from linearity should have been apparent. These results are in striking agreement with the early inertia wheel studies of Hill (1922) and Lupton (1922) and those of Dickinson (1928) during cycling, but are in direct contrast to the data of Wilkie (1950) describing the force-velocity behaviour of human arm muscles during isotonic loading. Nevertheless, the investigation by Wilkie (1950) has been criticized (Perrine and Edgerton, 1978) because the hyperbolic curve actually represents an external load-velocity relationship, and is not the true muscle force calculated from the load's immediate rate of acceleration. In fact, the values of force are calculated based on the assumption that human muscles in vivo will obey Hill's (1938) characteristic equation describing the force-velocity behaviour of isolated frog muscle. It has been suggested by Perrine and Edgerton (1978) that the shape of the force-velocity curve published by Wilkie (1950) may therefore be incorrect, and should perhaps have plateaued as it approached zero velocity.

In a recent study of afterloaded knee extensions, Tihanyi, Apor and Fekete, (1982) have also claimed to demonstrate a classical hyperbolic curve, relating external torque and angular velocity of movement. Maximal peak torque was recorded at six angular velocities ranging from aproximately 5.5 to 15.5 $rad \cdot s^{-1}$ (53 - 148 rpm), a similar range to that reported in this thesis. The hyperbolic nature of the relationship was caused by a level of maximal isometric torque (Po) which exceeded the torque generated at the slowest angular velocity by more than 100%. If the value of Po were excluded, the torque-velocity characteristic would be linear, in agreement with the results presented in this chapter.

The majority of recent studies have employed isokinetic resistance to create various constant velocities of movement and measured maximal voluntary force; force was usually acting about an axis of rotation and expressed as instantaneous torque. There have been two major reports of in vivo force-velocity relationships which resembled a classical hyperbolic curve. In 1973 Komi attempted to characterize the force-velocity behaviour of human forearm flexors and extensors and claimed that his data "follows closely the classical force-velocity relationship obtained with isolated muscle." However, the concentric force records presented by Komi in his figure 4 demonstrate a clear plateau, and even the suggestion of a decline at the three slowest velocities of contraction. A hyperbolic force-velocity relation has also been reported in human knee extensor muscles by Thorstensson, Grimby and Karlsson (1976). The study has attracted considerable criticism (Perrine and Edgerton, 1978; Gregor et al, 1979) however, because the torque-velocity curve was constructed from measurements of peak torque recorded at various joint angles (hence different muscle lengths) which prevents any meaningful comparison with results obtained in isolated muscles. Nevertheless, angle-specific measures of peak torque recorded by Thorstensson, Grimby and Karlsson (1976) in their table 1, would in fact generate a curve similar in shape to the one presented. At the same time, if the torque produced under isometric conditions were ignored the relation would be linear, in striking agreement with the results presented in this thesis.

Several other investigations of the torque-velocity behaviour of human knee extensor muscles in short range, single joint isokinetic movements (Moffroid et al, 1969; Perrine and Edgerton, 1978; Gregor et al, 1979; Wickiewicz et al, 1982) established that when the peak torque was measured at a specific joint angle the relationship was linear over a considerable portion of the range, but torque tended to level off at low velocities. The reason for the observed plateau is not known, but Perrine and Edgerton (1978) have suggested that it may be attributed to a neural regulatory mechanism which could restrict the muscles' maximum voluntary isometric tension to as little as 50% of their true peak capacity. It is unclear why there should be such a major discrepancy between the study of Thorstensson, Grimby and Karlsson (1976), and others, with regard to the shape of the torque-velocity curve at low velocities of movement. Unfortunately, the data presented here do not help to resolve the issue because testing did not take place at comparable slow velocities.

The studies mentioned thus far which employed isokinetic resistance were unable to measure peak torque at fast speeds of movement. The highest angular velocity reported (Ingemann-Hansen and Halkjaer-Kristenson, 1979) was 360°/sec (60 rpm) which is equivalent to approximately 52% of the maximal voluntary velocity for knee extension in that mode of testing (Thorstensson, Grimby and Karlsson, 1976). The only measurements of peak torque registered during isokinetic movements performed at high velocities have been made during stationary cycling (Sargeant, Hoinville and Young, 1981; this thesis). The maximal speed that an individual can pedal either a cycle ergometer (personal observations) or a bicycle during unloaded roller racing (Wilkie, 1960) is approximately 180 rpm (1080°/sec). Using an isokinetic ergometer peak torque has been measured in one subject up to 95% (1026°/sec) of this maximum by Sargeant, Hoinville and Young (1981), and up to 92% (996°/sec) in this thesis. In both studies the torque-velocity relationship was linear and gave no indication of levelling off at extremes of range. Despite this general similarity there were distinct differences in the results of the two investigations. The maximal peak torque generated at a given pedal crank velocity was considerably lower in the group of subjects studied by Sargeant, Hoinville and Young (1981). Although there was a quite wide inter-individual variation in the slope of the torque-crank velocity relationship in both studies it was more pronounced in the results described in this thesis. In the former investigation the force-velocity relationships "converged so that at zero force they intercepted the X-axis at 220±8 rev/min", but in the current work the extrapolated linear relationships intercepted the X-axis at various points from 220 to 409 rpm.

Consequently, Sargeant, Hoinville and Young (1981) demonstrated that the intersubject differences in peak torque in their study could be accounted for on the basis of variation in thigh muscle (+ bone) volume, whereas the data presented here could not be standardized by such a manoeuvre. This discrepancy suggests that there were physical dissimilarities between the two groups of subjects which may have contributed to the different results. One possible confounding variable may have been the underlying fibre type distribution of the muscles under test (discussed in detail in the next section). Indeed, the force-velocity relation reported by Sargeant, Hoinville and Young (1981) is very similar to that manifest by long distance runners, whereas the data included in this chapter are more representative of sprinters (Tihanyi, Apor and Fekete, 1982) (Appendix 1).

Experimental data from these studies cannot be fitted by the equation of a rectangular hyperbola (Hill, 1938), perhaps due to the fact that it was not possible to measure torque at low velocities of movement, or during an isometric contraction. Moreover, classical force-velocity testing was performed on isolated frog muscle, whereas the forces exerted on the pedal cranks during cycling result from the co-operative action of several muscles operating across at least two joints. The torque-velocity relationship described in this thesis must be considered "functional", and it seems unrealistic to attempt a precise mathematical comparison with the elegant work performed on isolated muscle.

3.4.4. Summary

Data were presented which described the torque-velocity behaviour of human leg muscles during maximal cycling exercise. Measurements of maximal peak torque were made at a series of pedal crank velocities representing approximately 81% of the functional range. The torque-velocity relationship was linear, and reproducible in a given subject. This finding is in agreement with other studies of in vivo torque-velocity behaviour which reported a linear characteristic over most of the range of velocities. The results indicated a positive relationship between thigh muscle volume (as determined from computerized axial tomography) and maximal peak torque output, but adjusting the data for active muscle mass did not reduce the overall variability, it merely altered the position of individuals in relation to the mean. The large differences in torque generation were not accounted for solely by the volume of active muscle. The torque-velocity relationship obtained during maximal cycling exercise over the range tested in this thesis does not appear to obey Hill's (1938) characteristic equation derived from studies on isolated frog muscle. The forces exerted on the cranks during cycling are produced by several muscles acting across at least two joints, and it seems inappropriate to expect the in vivo results to be directly comparable with the response of a maximally stimulated isolated musle shortening under an isotonic load.

3.4.5 Power-Velocity Relationships

The linear relationship between peak torque and pedal crank velocity reported in the previous section resulted in a parabolic power-velocity curve for each individual. However, the maxima occurred at various crank velocities between 120 and 160 rpm. In classical studies of isolated muscle, power is at a maximum when P/Po is 0.3 (Hill, 1938; 1964c). Unfortunately Po was not measured in the present investigation so it could not be determined directly whether the torque generated at the point of maximal peak power was equal to 0.3 Po. Nevertheless, if it is assumed that a similar relation governs the behaviour of muscles in vivo, then a theoretical mean value of Po may be calculated equal to 457, 440 and 445 N•m, in the subjects who achieved maximal peak power output at 120, 140 and 160 rpm, respectively (range from 368 to 549 N•m). These values are markedly higher than any published measurements of maximal isometric tension recorded with the Cybex apparatus (usual reported range 200 to 350 N•m). However, it is impossible to compare the absolute values of torque recorded on the CVE with those obtained on the Cybex because of the enormous difference in the length of the respective lever arms and accompanying variation in mechanical advantage. The maximal torque generated by one subject on the CVE was 349 N•m (215.7 kg) occurring at a crank velocity of 20 rpm. Thus one may speculate that a value of Po of 450 N•m may be quite realistic if the torque-velocity relationship were to become curvilinear at the slowest crank velocities. In any event it must be approximately correct because substituting a value of P/Po of 0.4 into the above calculations yields a value of Po ranging from 331 to 343 N•m, less than the measured peak torque that some subjects could generate at 20 rpm.

In several individuals the value of maximal instantaneous peak power generated by each leg separately was approximately three horsepower (2238 W), and in one subject as high as 3.49 hp (2604 W). Assuming that a similar power could be produced by each leg during a single bilateral movement the power output would be 6 - 7 hp (4476-5222 W). These values are somewhat greater than during a vertical jump (3902 W, Davies and Rennie, 1968). However, they are in good agreement with the maximal values calculated during sprinting at 11.46 yards a second (Furusawa, Hill and Parkinson, 1927b), and correspond closely to the theoretical limit for any practicable movement (Wilkie, 1960). In terms of measured, as opposed to calculated power, the data in this thesis appear to be higher than previously reported.

The power outputs recorded on the Cybex apparatus have been very low (Thorstensson, Grimby and Karlsson, 1976; Perrine and Edgerton, 1978), due largely to the limited velocity range of the instrument. However, the data do concur with the findings reported here, which demonstrate a relative plateau in power at the three fastest crank velocities. This is in marked contrast to the work of Sargeant, Hoinville and Young (1981) which indicated that each of their five subjects achieved maximal power output at 110 rpm. Such a discrepancy may be due to a more heterogeneous subject population used in the present study. At the same time it could result from a potential weakness in the design of the ergometer employed by Sargeant, Hoinville and Young (1981) (discussed in section 1.7).

The considerable inter-subject variability in the capacity to generate high levels of torque and hence power at fast crank velocities may be related to additional factors, including the proportion of Type II fibres in the exercising muscle. Type II fibres are known to have faster contraction times and rate of tension development than Type I fibres (Burke et al, 1973), and are more dependent on glycolysis to maintain adequate levels of ATP, rather than the slower process of oxidative phosphorylation, (Essen et al, 1975). It was not a major purpose of this study to examine the relationship between muscle fibre types and the ability to generate high levels of power at fast crank velocities. However, it was considered worthwhile to take a sample of muscle from two subjects (BL and MS in figures 16 and 24) who were representative of the greatest differences in power output at fast crank velocities. Three needle biopsy samples (Bergstrom, 1962) were taken from two sites in the right (dominant) vastus lateralis muscle of each subject to determine fibre type distribution by a modified myofibrillar ATPase method (Guth and Samaha, 1969); approximately 3000 fibres were counted for each subject. In subject BL, who achieved a maximal peak power output of 2539 W at a crank velocity of 162 rpm, 72% of the fibres were Type II (Fig. 25); whereas subject MS, who attained a maximum value of 1708 W at 119 rpm, possessed 53% Type II fibres (Fig. 25).

These limited results concur with the findings of Thorstensson, Grimby and Karlsson (1976), who demonstrated a significant positive relationship between maximal peak power generated at the fastest angular velocity of the Cybex lever arm (180°/sec), and the percentage of Type II fibres in the knee extensor muscles. A similar correlation has been confirmed in athletes (Thorstensson, 1976; Gregor et al, 1979) and non-athletes (Coyle, Costill and Lesmes, 1979). Moreover, such data are in accordance with the contractile properties of isolated animal (Wells, 1965) and human (Faulkner, Jones, Round and Edwards, 1980) muscle, and the

Figure 25. Fibre type distribution in two subjects (BL and MS in figures 16 and 24) who were representative of the greatest differences in power output at fast velocities. In subject BL 72% of the fibres were Type II whereas subject MS possessed 53% Type II fibres.

empirical observations on muscle fibre types in athletes and sedentary individuals (Gollnick et al, 1972; Appendix 1). A greater inter-subject variability in fibre type distribution may be one possible reason why the power-velocity data in the present work could not be standardized by making adjustment for muscle volume, whereas Sargeant, Hoinville and Young (1981) observed that differences in muscle (+ bone) volume were sufficient to account for most of the variation in power output in their group of subjects, who were homogeneous in fibre type.

3.4.6 Summary

The maximal peak instantaneous power generated by human leg muscles was calculated from the measurements of peak torque made over a wide range of constant velocities of the pedal cranks. Maximal peak power was a parabolic function of crank velocity, with the maxima occurring from approximately 120 to 160 rpm. Maximal isometric tension was not measured, but calculated based on relationships demonstrated in isolated muscles. This calculation afforded reasonable agreement with classical studies by indicating the probability that maximal power output during cycling was generated when P/Po was approximately equivalent to 0.3 - 0.4. However, it must be noted that this calculation was based on the assumption that the high torque, low velocity portion of the torque-velocity relationship would be curvilinear, and not exhibit a plateau in torque as reported by some investigators.

The maximal levels of peak power observed in this study appear to be higher than previously reported. The variation in crank velocity for the generation of maximal power is in direct contrast with previous measurements made during cycling (Sargeant, Hoinville and Young, 1981). A greater inter-subject variation in fibre type in the present investigation may be one possible factor which contributed to the discrepancy.

4.0 POWER OUTPUT AND FATIGUE OF HUMAN MUSCLE IN MAXIMAL CYCLING EXERCISE

4.1 Introduction

In the historical review which begins this thesis the point is made that there is a vast amount of research literature concerned with physical exercise of submaximal intensity, yet the information on maximal work of short duration is very scarce. Studies which reported measures of maximal power output have usually involved activities in which the subject first overcame a considerable inertia and then performed at maximal speed until completion of a fixed amount of work, or duration of effort. As discussed by Wilkie (1960), in this situation the load is not suitably matched to the muscles "so as to exploit to the full their intrinsic force-velocity relationship." Moreover, the maximum power output capacity of muscles at different speeds of limb movement cannot be measured. The work described in this section was intended to overcome these difficulties; one of the objectives was to measure the external work and power generated by the legs throughout 30 seconds of maximal cycling on the CVE at various constant velocities of the pedal cranks.

In isolated muscles stimulated to shorten against a constant load the optimum mechanical efficiency occurs when the force is equal to fifty percent of the maximal isometric tension (P/Po = 0.5) (Hill, 1964c). Thus the force is somewhat greater, and the velocity of shortening somewhat less, than during the production of peak power (P/Po = 0.3). This relationship led to the hypothesis outlined in chapter one (section 1.10), that during repeated maximal voluntary isokinetic contractions of human muscles the reduction in force would be relatively greater during rapid movements than during slower ones. This hypothesis was tested in the present study by examining the effects of pedal crank velocity on the power output and fatigue of leg muscles during maximal cycling exercise of 30 seconds duration. Finally, the concentration of lactate in venous plasma has been demonstrated by Karlsson (1972) to yield an approximate index of the exercising muscles' production of lactate from glycolysis. Thus it seemed appropriate to investigate whether maximal intensity pedalling performed at different rates was accompanied by a common level of lactate production.

4.2 Methods

4.2.1 Subjects

The 12 individuals who acted as subjects in the study of torque-velocity relationships, plus one other, (Appendix 7) participated in the investigation.

4.2.2 Experimental Protocol

The standard procedures described in chapter two (section 2.1.6) were employed in the study. Three crank velocities were selected to provide a range from slow (60 rpm), to intermediate (100 rpm) and fast (140 rpm). The sequence of velocities was chosen at random and during each test the subject was encouraged to exert maximal force on the pedals of the CVE for 30 seconds. Tests were separated by at least one day; in addition each subject performed a repeat test at one crank velocity, selected at random, to study the day-to-day variability in performance.

Factors which might influence performance and had been measured previously were each individual's maximal oxygen uptake (section 3.2.3) and thigh muscle volume (Appendix 7). Three minutes following completion of the test a venous blood sample was taken from an antecubital vein for subsequent analysis of plasma lactate concentration by a fluorimetric enzymatic technique (Hohorst, 1965).

4.2.3 Calculation of Torque, Work and Power

Peak torque and power were calculated as previously outlined (sections 2.1.4 and 3.2.5). In addition, the area under the force record was obtained using a Talos digitizer in series with a microprocessor (Compucolor II RS 232), for the measurement of work (J) and average power (W) during each pedal stroke. A fatigue index (FI) similar to that devised by Thorstensson and Karlsson (1976) was used to quantify the extent of decline in power during the 30 s of the test:

$$\text{fatigue index} = \frac{\text{initial power} - \text{final power}}{\text{initial power}} \times 100$$

where initial power was the mean of the 3 pedal strokes which represented the highest observed power output and final power was the mean of the last 3 pedal strokes in the test. In addition, the absolute rate of decline in power (initial-final $W \cdot s^{-1}$) was calculated.

4.2.4 Statistics

A randomized block analysis of variance (anova) was selected to examine the relationships between crank velocity, maximal power, fatigue, and total work performed during the four 30 s tests. Analysis of covariance was used to investigate the associations between the maximal values of peak power and average power, FI, rate of decline in power, total work and the following variables - $\dot{V}O_2$ max, thigh muscle volume, and venous plasma lactate concentration. The relationships within each crank velocity were examined by a Pearson correlation analysis. The repeat values for maximal torque, power, total work and the FI were compared using Student's t-test for matched pairs (2-tailed test), and a coefficient of variation was computed for values obtained at each crank velocity.

4.3 Results

4.3.1 Maximal Torque and Power

A summary of the torque, work and power output data is displayed in Table 1, together with calculations which describe the extent of fatigue, and values of plasma lactate obtained three minutes following exercise; individual results are listed in Appendix 7. Peak torque (hence peak power) generated by each leg at 60 rpm was almost identical, but the right leg achieved a slight dominance at the faster pedalling speeds (Fig. 26; Table 1).

As in the previous study of torque-velocity relationships the maximal peak torque was inversely related to pedal crank velocity ($p < 0.0005$), whereas the maximal peak power increased with pedalling rate ($p < 0.0005$). Also in agreement with the earlier investigation the measures of maximal peak

Table 1. Power output and fatigue data (mean ±SD). All results except 5, 10 and 11, were calculated from the mean values obtained during three successive pedal cycles.

VARIABLE	REVOLUTIONS PER MINUTE		
	60	100	140
1. MAXIMUM PEAK TORQUE (N·m)	197.1 ± 21.6	142.6 ± 14.8	109.7 ± 19.1
2. MAXIMUM PEAK POWER (W)	1171.2 ±134.3	1465.6 ±164.4	1548.7 ±277.0
3. MAXIMUM AVERAGE POWER (W)	757.7 ± 99.5	964.2 ±121.2	1049.9 ±172.5
4. MAXIMUM WORK (J)	800.7 ± 97.9	588.4 ± 69.8	467.4 ± 75.4
5. TOTAL WORK (KJ)	20.363 ± 2.542	21.828 ± 2.712	21.068 ± 3.849
6. FATIGUE INDEX-PEAK TORQUE & POWER (%)	23.6 ± 5.7	45.7 ± 8.0	59.3 ± 6.2
7. FATIGUE INDEX-AVERAGE TORQUE, WORK & AVERAGE POWER (%)	23.7 ± 4.6	47.7 ± 5.7	58.7 ± 6.5
8. RATE OF PEAK POWER DECLINE ($W \cdot s^{-1}$)	11.6 ± 4.1	24.5 ± 5.4	32.4 ± 7.5
9. RATE OF AVERAGE POWER DECLINE ($W \cdot s^{-1}$)	7.5 ± 1.9	17.3 ± 3.4	21.6 ± 5.1
10. AVERAGE POWER SUSTAINED FOR 30 SECONDS (W)	678.8 ± 84.7	727.6 ± 90.4	702.3 ±128.3
11. PLASMA LACTATE (mmol/litre)	9.68± 2.83	10.57± 2.55	9.15± 2.68

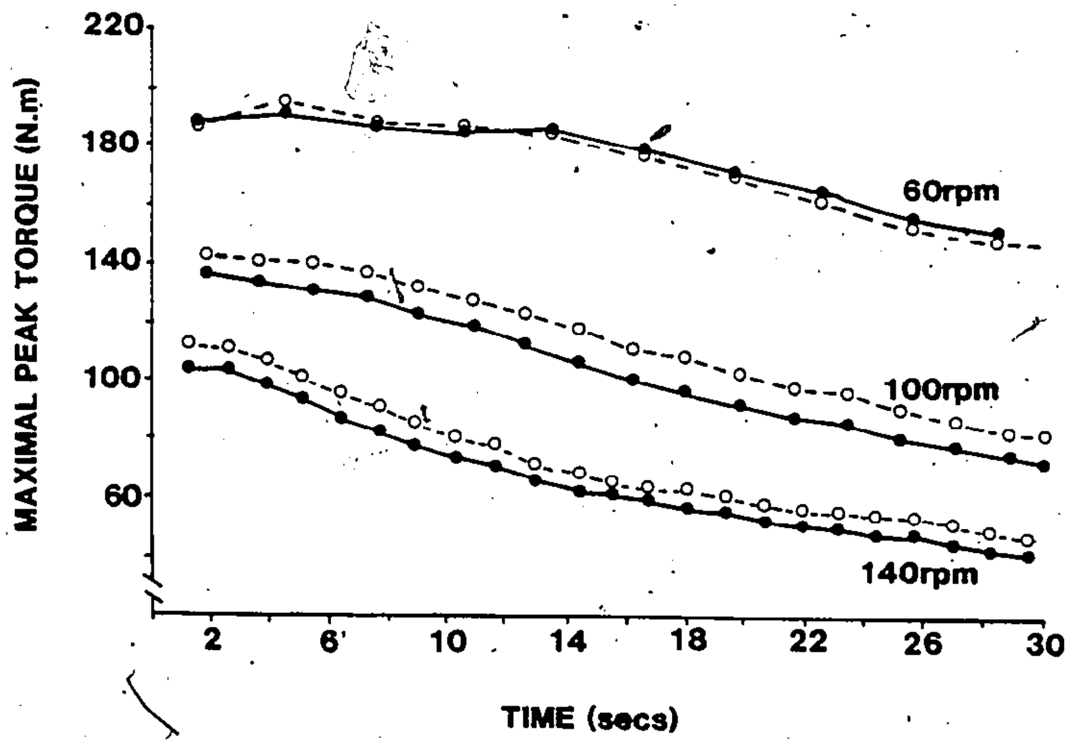


Figure 26. Measurements obtained in 13 subjects of peak torque produced by each leg during 30 s of maximal cycling at 60, 100 and 140 rpm. Values are the mean of three consecutive pedal cycles; error bars are omitted for the sake of clarity. o————o right leg; •————• left leg.

torque and power were positively associated with each individual's thigh muscle volume ($p=0.013$). One question of interest was whether the measures of peak instantaneous power recorded in a given individual were closely related to the average power obtained by integrating the area under the force record. The two measures of power were closely related, both increasing linearly with pedalling rate (Fig. 27). Thus it appears that either the instantaneous or integrated power may be used to describe accurately inter-individual differences in performance. Although the maximal peak and average power output was achieved at the fastest pedalling speed the average power that could be maintained throughout the entire 30 s test showed a descending sequence from 100 rpm to 140 rpm and 60 rpm (Table 1; Fig. 28). However, the differences between the three velocities were not significant.

4.3.2 Fatigue Index

The fatigue index (FI) for both peak and average power was significantly different between the three tests ($p< 0.0005$) (Table 1) and increased linearly with pedal crank velocity (Fig. 29). The relative decline in peak power was highly correlated with the relative decline in average power ($r = 0.93$; Fig. 29) and the values for the FI at each velocity were almost identical. This confirmed the obser-

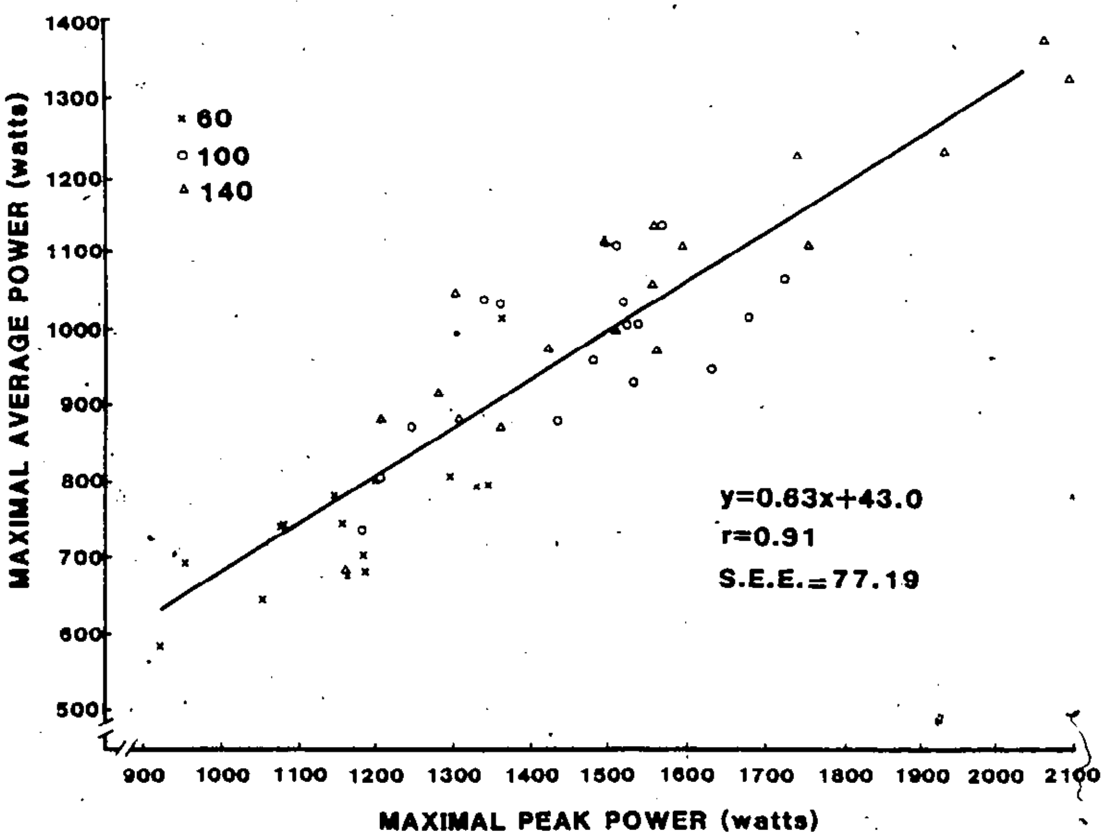


Figure 27. -The relationship obtained in 13 subjects between the maximal peak power (mean of both legs) and maximal average power (sum of both legs) generated during cycling at 60, 100 and 140 rpm. The values are the mean of three consecutive pedal cycles. The high correlation between the two measures indicates that either maximal peak or average power may be used to describe accurately inter-individual variation in performance.

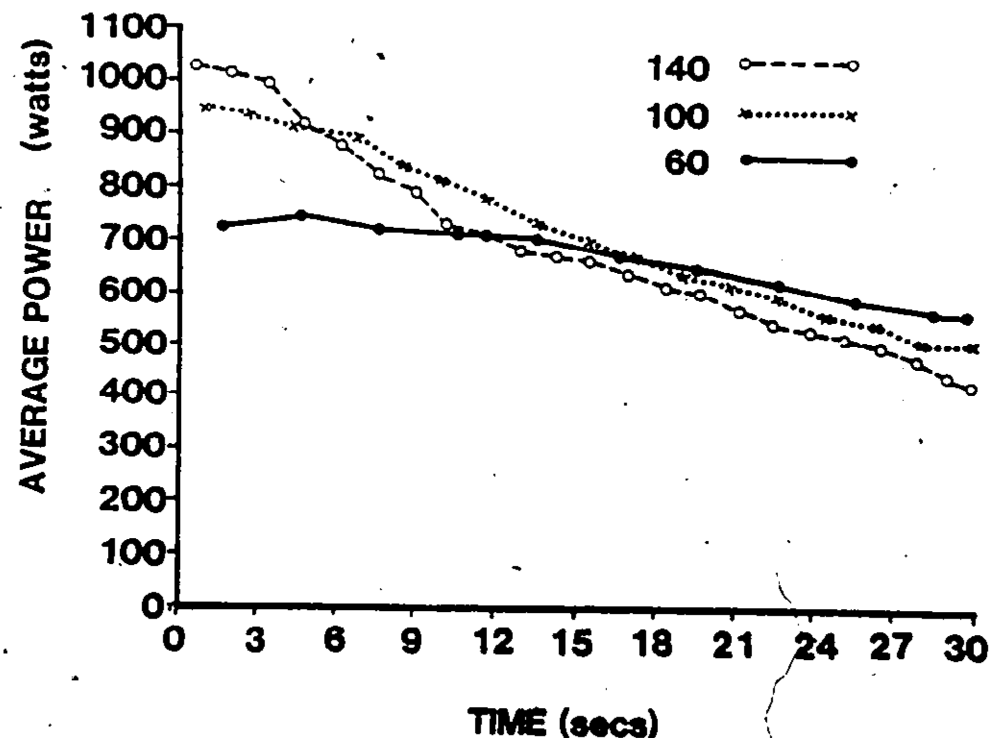


Figure 28. Decline in average power (sum of both legs) during 30 s of maximal effort by 13 subjects at crank velocities of 60, 100 and 140 rpm. The values are the mean of three consecutive pedal cycles normalized for time. Error bars are omitted for the sake of clarity.

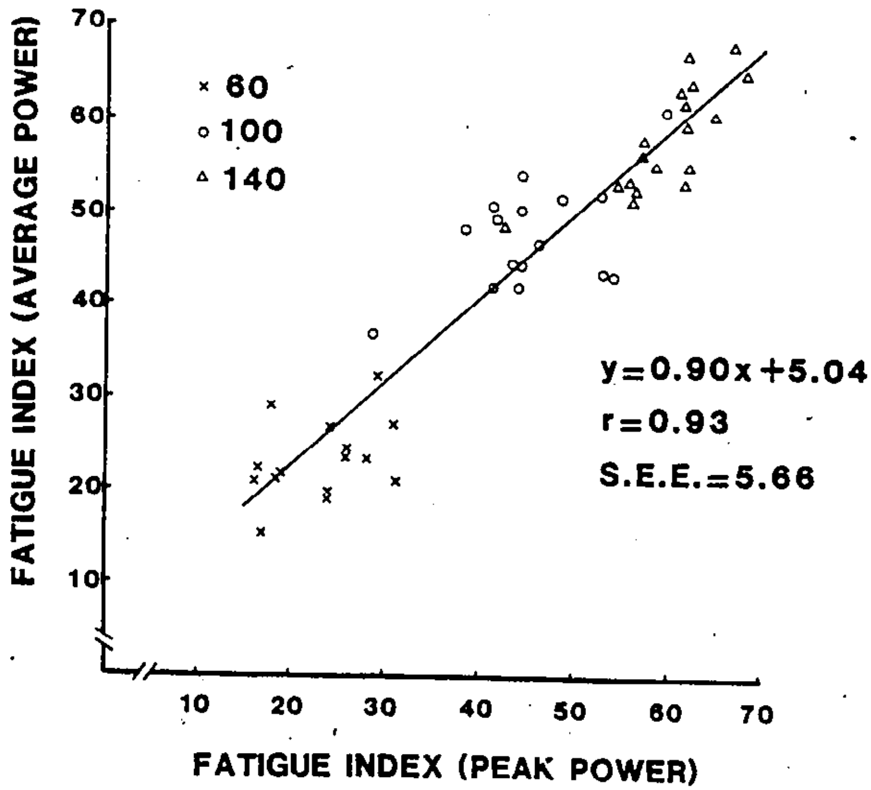


Figure 29. The relationship obtained in 13 subjects between the fatigue index for peak ~~power~~ and average power, during 30 s of maximal effort at 60, 100 and 140 rpm.

vation in the preceding section, that results pertaining to either the peak instantaneous or integrated power may be employed to characterize the performance of subjects.

Relationships between variables were also examined separately within each velocity. At a pedalling rate of 60 rpm there was a significant negative correlation between the FI for peak power and $\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$) ($r = -0.63$, $p < 0.0006$). Such an association was not evident at the faster crank velocities ($r < 0.1$).

4.3.3 Rate of Decline in Power

The rate of decline in power ($W \cdot s^{-1}$) at each velocity reflected the results for the FI (Table 1); as crank velocity increased, the rate of decline in both peak (Fig. 30, 31) and average power (Fig. 31) increased similarly ($p < 0.0005$). Once again, there was a high correlation between the rate of decline in peak power at the three pedalling speeds, and the rate of decline in average power ($r = 0.93$, $p < .0005$) (Fig. 31). There was also a strong correlation between the maximal peak power output and the rate of decline in peak power ($r = 0.86$, $p < 0.0005$), average power ($r = 0.81$, $p < 0.0005$), and the total amount of work performed during each test ($r = 0.66$, $p < 0.0005$).

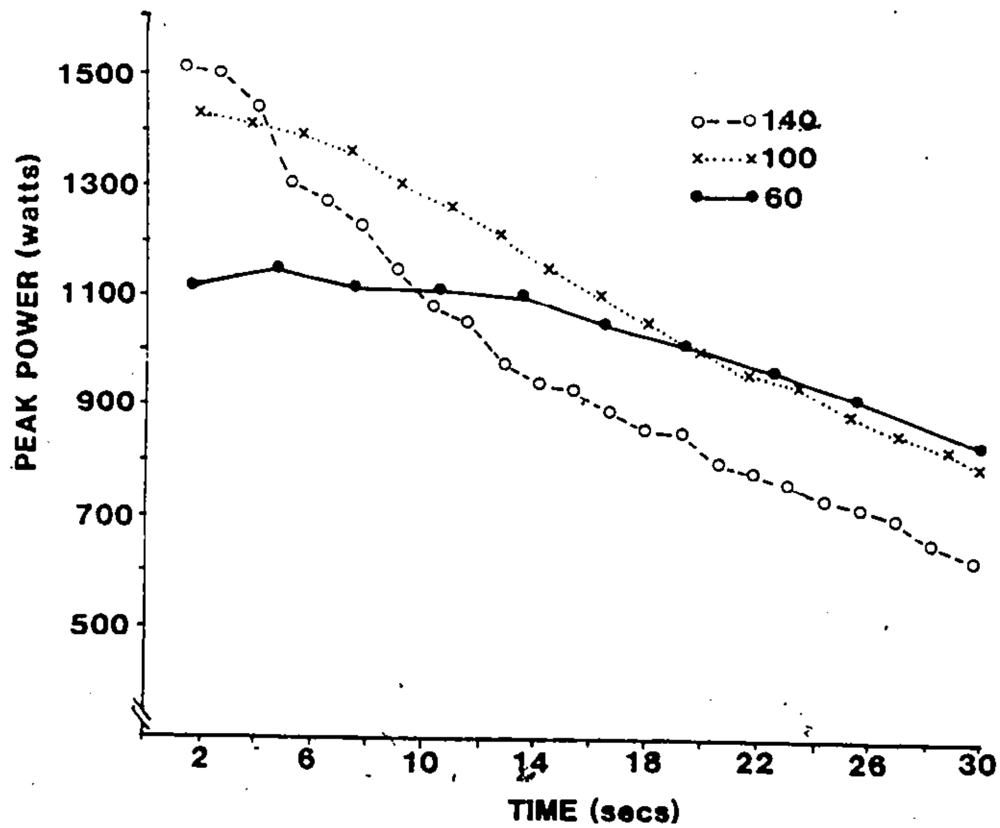


Figure 30. Decline in peak power (mean of both legs) during 30 s of maximal cycling by 13 subjects at crank velocities of 60, 100 and 140 rpm. Values are the mean of three consecutive pedal cycles normalized for time. Error bars are omitted for the sake of clarity.

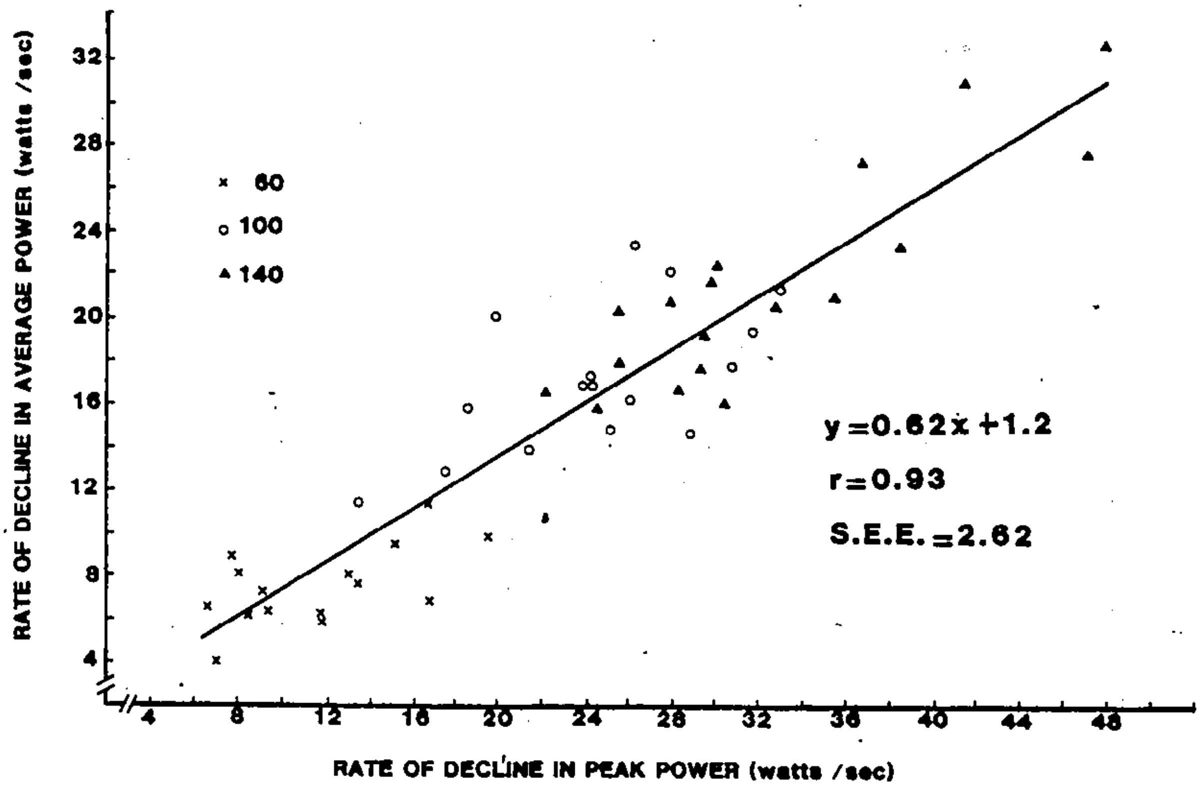


Figure 31. The relationship in 13 subjects between the rate of decline in peak power (mean of both legs) and average power (sum of both legs), during 30 s of cycling at 60, 100 and 140 rpm.

4.3.4 Work and Total Work

The mean maximum amount of work that could be generated during three complete revolutions of the pedal cranks was inversely related to velocity, and thus positively related to the duration of contraction (Table 1). Consequently, the maximal work generated at 60 rpm was 36 and 71% greater than at 100 and 140 rpm respectively ($p<0.0005$). Total work output during the 30 seconds, however, was not significantly different between the three crank velocities. Nevertheless, the pattern of work during the test was influenced substantially by pedalling rate. This is demonstrated clearly in figure 32 which depicts the amount of work accomplished during each successive five second period of cycling at the three crank velocities. During the initial five seconds most work was achieved at 140 rpm and least at 60 rpm. Thereafter the work generated at 140 rpm decreased sharply, and more work was produced at 100 rpm in each additional five second interval throughout the test. The work output at 60 rpm decreased comparatively little during the half-minute of cycling, and the amount produced after fifteen seconds was greater than at the other two pedalling frequencies. Even so, the early advantage that was gained by performing at 100 and 140 rpm resulted in a total work that was slightly higher than that accomplished at the slowest speed.

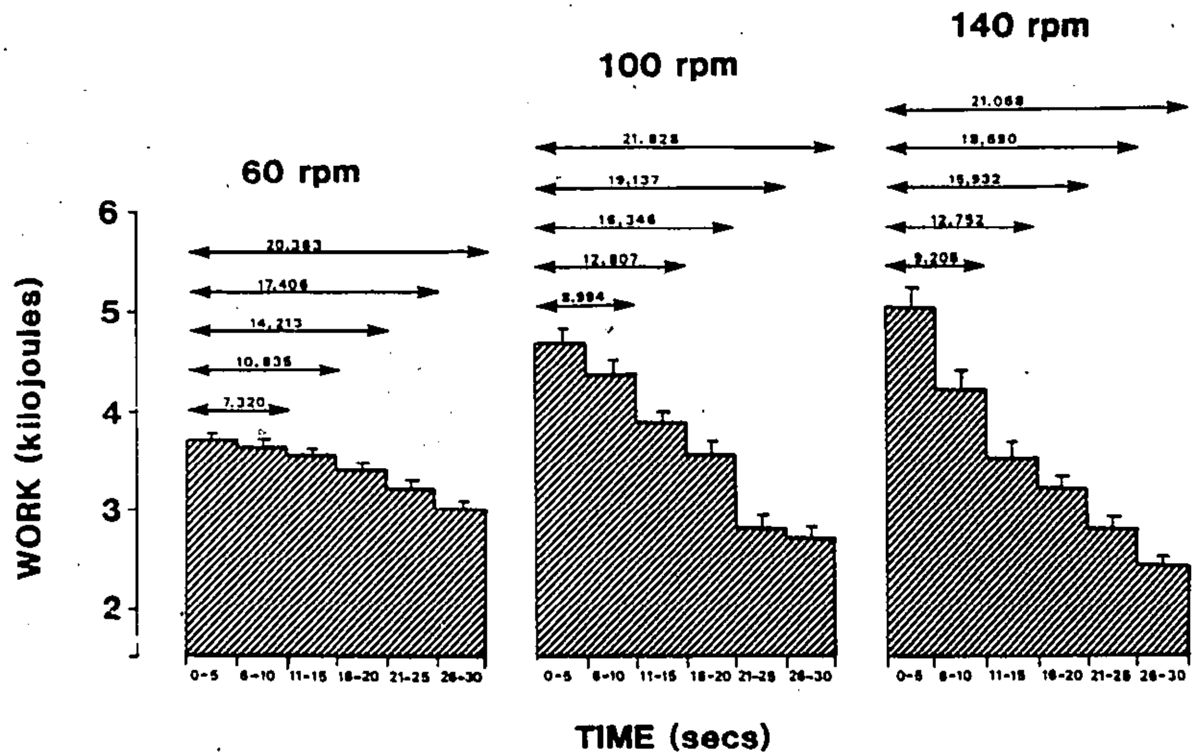


Figure 32. Total work (mean ±1 S.E.M.) generated in each consecutive five second period of a maximal effort 30 s test at 60, 100 and 140 rpm. ←——→ denotes cumulative work throughout the test.

4.3.5 Plasma Lactate

Values of venous plasma lactate taken three minutes post-exercise (Table 1, 28) were not significantly different between the three crank velocities.

4.3.6 Repeatability of Measurements

A paired t-test indicated no significant differences in any power output variable measured during repeat tests at any of the three pedalling frequencies ($p > 0.5$). The mean coefficient of variation for maximal peak power, maximal average power, FI and the total work at all crank velocities was 8.6, 9.6, 14.5 and 9.6% respectively. Average power generated throughout the repeat tests was very similar on both occasions (Figs. 33 to 35)

4.4 Discussion

4.4.1 Introduction

As outlined in the first chapter of this thesis (section 1.10) the present work was designed to yield more complete information on the ability of muscles to engage in short-term maximal exercise. Specifically, the study examined the effects of pedalling speed on the power output, total work and fatigue during 30 seconds of maximal cycling exercise on the CVE.

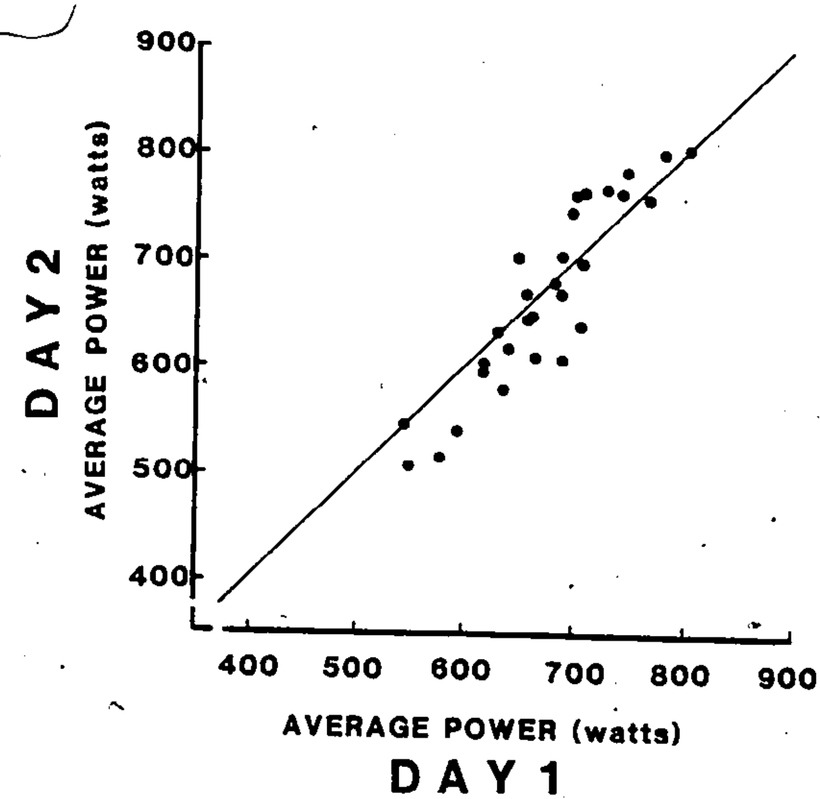


Figure 33. Measurements obtained in 3 subjects of average power generated by both legs during 30 s of maximal effort at 60 rpm on two occasions, at least 24 hours apart. Values are the mean of three consecutive pedal cycles. The line shown is the line of identity.

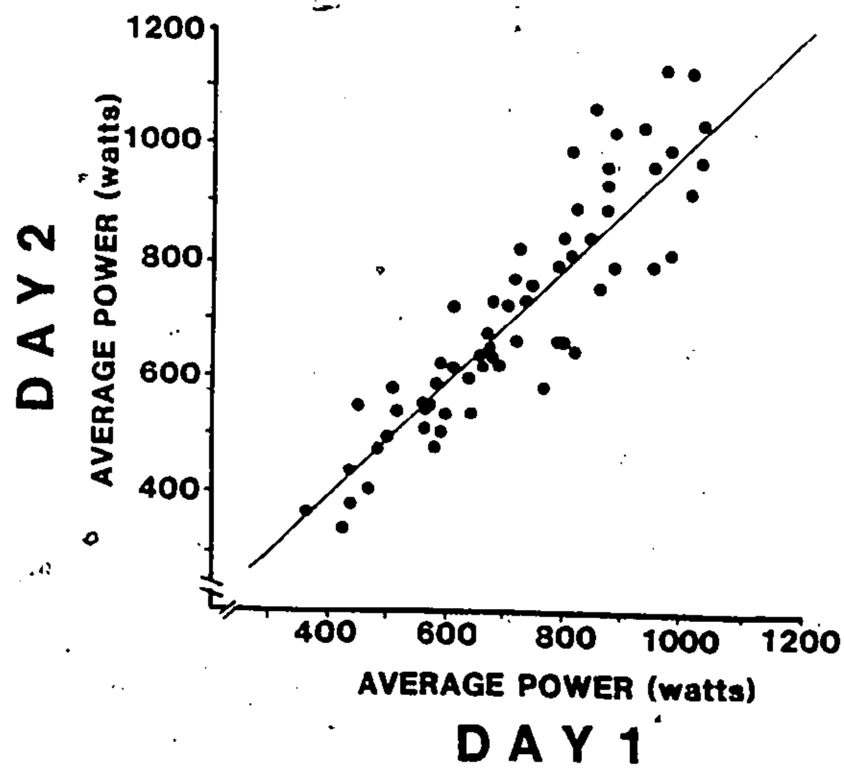


Figure 34. Measurements obtained in 4 subjects of average power produced by both legs throughout 30 s of maximal cycling at 100 rpm on two occasions, at least 24 hours apart. Values are the mean of three consecutive pedal cycles. The line shown is the line of identity.

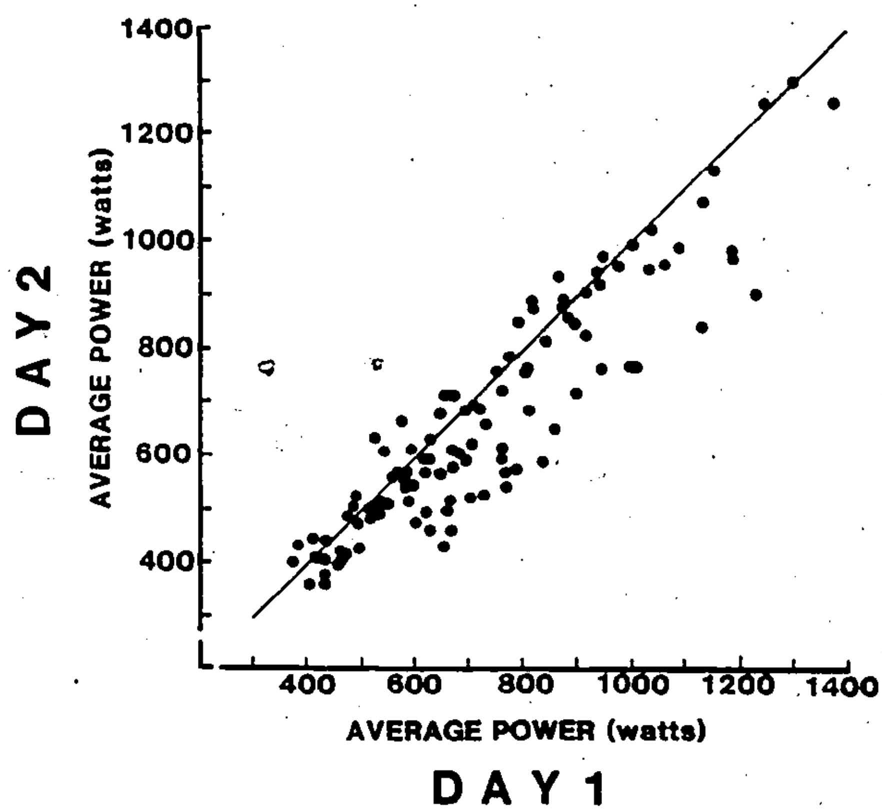


Figure 35. Measurements obtained in 5 subjects of average power generated by both legs during 30 s of maximal effort at 140 rpm on two occasions, at least 24 hours apart. Values are the mean of three consecutive pedal cycles.

4.4.2 Peak Power and Average Power

It has been argued by Moffroid et al (1969) that because muscular torque varies through an arc of motion, maximal instantaneous power is a more definitive measure of muscular performance at different velocities of movement than average power. In the present study however, the values of peak instantaneous power were highly correlated with the measures of average power obtained by integrating the area under the force record. Consequently, the extent of decline in peak and average power was similar at a given crank velocity. These data confirm that either the peak instantaneous torque and power, or the average values may be employed to describe intra and inter-individual differences in performance. Similar high correlations have also been obtained during maximal knee extensions on the Cybex apparatus (Nilsson, Tesch and Thorstensson, 1977).

4.4.3 Repeatability of Measurements

In all studies reported in this thesis subjects performed duplicate tests on separate days, in order to establish that the results obtained in a given individual were reproducible on another occasion. In the present work subjects performed a repeat test at one pedalling speed, selected at random, and there were no significant differences in any power output variable measured on the two days. The coefficients of variation were very similar to those published previously for repeated tests of maximal strength, and power (Tornvall, 1963; Thorstensson, 1976). These data confirmed that the CVE was a sensitive, reliable instrument for measuring maximal external power output during isokinetic cycling exercise.

4.4.4 Crank Velocity, Power Output, Work and Fatigue

In agreement with earlier classical studies of frog (Hill, 1938) and human muscle mechanics (Hill, 1922) the present results indicated that the maximum work generated in a single revolution of the pedal cranks was positively related to the duration of movement (hence contraction), whereas the mean maximal power output increased with pedalling rate over the range tested.

Although increases in crank velocity were associated with a significantly higher initial power they were also accompanied by a greater rate and extent of decline in power. After approximately 12 and 17.5 seconds the sustained power output at 60 rpm became greater than at 140 and 100 rpm, respectively (Fig. 28). Thus at faster crank velocities more external work was produced early in the test; but in the later stages more external work was accomplished at the slowest pedalling speed (Fig. 32). This changing pattern of power output resulted in minimal differences in the total amount of work produced at the three crank velocities during the entire 30 seconds. The concomitant mean average power output ranged from 678.8 to 727.6 W, in close agreement with values calculated during very brief periods of running upstairs (Unna, 1946; Margaria, Rovelli and Aghemo, 1966), and measured during 30 seconds of cycling on a constant-work-rate ergometer (Wilkie, 1981).

The significantly greater decline in power at higher rates of constant velocity movement in the present study appears to have been reported only once before. In their investigation of torque-velocity relationships during cycling on a similar isokinetic ergometer, Sargeant, Hoinville and Young (1981) noted that power declined throughout 20 seconds in a manner which appeared to be velocity dependent. This is in distinct contrast to the work of Barnes (1981) who reported that isokinetic fatigue curves for 10 consecutive knee extensions on the Cybex apparatus were not significantly different, regardless of lever arm velocity. However, the fastest angular velocity investigated by Barnes (1981) was less than one third that employed in either the present study or by Sargeant, Hoinville and Young (1981). Moreover, many fewer contractions were investigated by Barnes (1981) and the rest interval between movements was standardized, so it is difficult to compare the studies directly. Nevertheless, during cycling at 60, 100 and 140 rpm, 30 cycles were completed in 30, 18 and 12.9 seconds respectively, and the fatigue index at those time points was still significantly greater at the higher crank velocities. The mean decline in power after 30 pedal cycles at 60 rpm was 23.6 percent, at 100 rpm 28.2 percent, and at 140 rpm 34.6 percent. Thus the fatigue incurred during maximal cycling increased with pedalling rate, regardless of whether comparison was made over time or a defined number of pedal revolutions.

It is not possible to identify the cause of the greater fatigue registered during pedalling at fast speeds in the present study. A diminished capacity to generate muscle force may result from reduced motor unit activation, or from metabolic factors which inhibit the rate of ATP utilisation.

In 1922 Hill defined the mechanical efficiency of muscular contraction as the external work done/energy used up and subsequently demonstrated by thermal measurements (Hill, 1939; 1964c) that it was optimal in frog muscle when the force was somewhat greater, and the velocity of shortening somewhat less (P/Po = 0.5), than during the production of peak power (P/Po = 0.3). Such a relationship led to the hypothesis outlined in chapter one (section 1.10), that fatigue during maximal cycling performed at fast pedalling speeds should be greater than at slow speeds. The data support the hypothesis; the significantly greater rate and extent of decline in power at higher crank velocities is suggestive of a decreased mechanical efficiency. Currently, the (thermodynamic) efficiency of muscular contraction is defined as the external work divided by the free energy (Wilkie, 1960a; 1974). It is claimed that an approximate determination of the free energy may be obtained in man during submaximal steady-state exercise by measuring oxygen intake and relating it to biochemical changes in the muscle (Whipp and Wasserman, 1969), but this was not attempted in the present study. Nevertheless, there have been many reports of submaximal cycling exercise performed on a stationary ergometer which noted a decrease in the calculated muscular efficiency with increments in speed above the optimum rate of 50 to 60 rpm (Duffield and McDonald, 1923; Cathcart, Richardson and Campbell, 1923; Pugh, 1974, Gaesser and Brooks, 1975; Seabury, Adams and Ramey, 1977). Few studies however, have examined frequencies of movement equivalent to greater than 120 rpm. Exceptions are the work of Hill (1922) on the elbow flexors, and Dickinson (1929) on the leg muscles during cycling. In both studies the mechanical efficiency during maximal (Hill, 1922) and submaximal (Dickinson, 1929) contractions equivalent to 60, 100, and 140 rpm was 18.7 to 21.5, 7.5 to 11.5 and 1 to 3 percent, respectively.

A large decrease in mechanical efficiency at higher pedalling rates would result in a greater expenditure of free energy for a given amount of external work, together with an increased waste of potential energy in the form of heat. Under these conditions relatively more free energy would be required to maintain performance. During maximal exercise of short duration, energy is supplied almost exclusively from the degradation of phosphorylcreatine (PC) and from glycolysis (Newsholme, 1978). Experiments on frog muscle have demonstrated that the breakdown of PC and glycogen over a cycle of contraction and relaxation is directly proportional to the sum of the heat and the work produced (Wilkie, 1968), and the heat production during isotonic contraction is greatest when the work is maximal (Fenn, 1923). In the present study during the initial stages of cycling at the fast crank velocities the work (and by inference the heat production) was greatest. This may have resulted in an increased rate of degradation of PC and glycogen, and greater changes in metabolic substrates and products which in turn could have exerted inhibiting effects on the biochemical processes associated with muscle contraction. An increased rate of glycolysis would result in a greater production of hydrogen ions, which have been implicated as a major cause of fatigue during activities requiring maximal power (Hermansen, 1981). Hydrogen ions have been demonstrated to inhibit the activities of rate-limiting enzymes in the glycolytic pathway (Gevers and Dowdle, 1963), to compete with calcium ions for the binding site on troponin C (Fuchs, Reddy and Briggs,

1970) and also may prevent the release of calcium ions from the sarcoplasmic reticulum (Nakamura and Schwartz, 1972), thereby interfering with excitation contraction coupling. Recently, using the technique of nuclear magnetic resonance Dawson and her colleagues (1978) established that in repetitively tetanized frog muscle a more frequent pattern of stimulation resulted in a more rapid utilization of total phosphorus, and a faster production of lactate. They suggested that the decline in isometric force was the result of decreasing ATP utilisation, potentially caused by product inhibition or decreased calcium release.

In the present investigation the high lactate concentrations in samples of venous plasma taken three minutes post-exercise were not significantly different at the three crank velocities. Although this finding suggests that a common rate of glycolysis was present during the three exercise bouts, lactate concentration in one sample of venous plasma may not accurately reflect muscle lactate production. A follow-up study in a group of five subjects demonstrated that plasma lactate concentrations 4 to 10 minutes following thirty seconds of maximal cycling at 140 rpm were significantly higher than at 60 rpm, although similar prior to three minutes (Appendix 4). Certainly, the significantly greater initial power output and subsequent rapid fatigue observed at higher pedalling speeds could be explained by an early increased rate of energy turnover which quickly became insufficient to keep up with demand. However, there are other equally plausible alternatives to account for the results.

The greater rate of fatigue noted at the faster crank velocities may have resulted from a greater relative contribution to force output by fast twitch motor units. It is generally agreed that in most physiological circumstances motor unit recruitment during muscular contraction occurs in an orderly sequence according to the Size Principle proposed by Henneman and colleagues (1965; 1965a), but an alteration of recruitment pattern may occur under some circumstances (Grimby and Hannerz 1977; 1981; Garnet and Stephens, 1978; 1981). In fast ramp contractions however, it has been reported (Desmedt and Godaux, 1977; Budingen and Freund, 1976) that there is a decrease of the threshold force with increasing rate of rise of tension, resulting in a temporal compression of the recruitment range of motor units and an early activation of all units. Moreover, during very rapid (ballistic) contractions, and isotonic movements, motor units which are recruited at widely different force thresholds in slow ramp contractions may be activated in a high frequency (60 - 120 Hz) transient burst which may even precede the production of muscle force (Desmedt and Godaux 1977; 1977a; 1979). Thus during rapid contractions fast twitch motor units are recruited earlier and attain higher firing frequencies than in slow movements. It is clearly established in animal preparations that individual fast twitch motor units are capable of greater levels of tetanic tension, but are more prone to fatigue, than slow twitch motor units (Burke et al, 1973). Similar results have been obtained during maximal voluntary dynamic contractions of human muscles with a high percentage of Type II fibres (Thorstensson and Karlsson, 1976; Thorstensson, Grimby and Karlsson, 1976).

In the present study no attempt was made to measure motor unit activity, but indirect evidence was obtained which suggested tentatively that the contribution of different fibre types to whole muscle tension may have varied between slow and fast crank velocities. A significant negative correlation ($r = -0.63$, $p<0.006$) existed between maximal oxygen uptake and the fatigue index for peak power output at a crank velocity of 60 rpm, but not at 100 and 140 rpm. This is in agreement with the results of a preliminary study outlined in chapter 2 (section 2.2), which indicated a similar relationship ($r = -0.84$) in a group of 17 young male subjects who performed a maximal effort test on the CVE for 45 seconds at 60 rpm (Appendix 3). These data suggest that the muscle's oxidative capacity may be important in determining the extent of fatigue during maximal cycling exercise at slow crank velocities; this in turn may suggest a major contribution by

Type I fibres. Support for this suggestion is provided by the results of a recent study (Ivy et al, 1982), in which it was demonstrated that individuals with a large proportion of Type I fibres in the vastus lateralis muscle also possessed both a higher maximal oxygen uptake, and muscle respiratory capacity, than those individuals who contained less than the average number of Type I fibres. Moreover, the respiratory capacity of the muscle appeared to be a major determinant of the rate and extent of fatigue during 45 s of repeated maximal isokinetic knee extensions on the Cybex apparatus, performed at an angular velocity of 180°/s (30 rpm); a high respiratory capacity was associated with a significantly smaller decline in power.

During fatigue at 60 rpm peak instantaneous power was generated consistently when the pedal crank was at the forward horizontal (90°) position whereas during fatigue at 100 and particularly 140 rpm, peak power was produced later, when the crank was between approximately 115° and 140°. This suggests that fatigue at high crank velocities was associated with a decrease in muscle contraction speed and rate of tension development. These results could be attributed, at least in part, to a selective drop-out and fatigue of Type II muscle fibres. Similar conclusions were reached by Nilsson et al (1977) during a study of repeated fast maximal voluntary isokinetic contractions of the knee extensor muscles.

A progressive reduction in motor unit activation has been observed during a maximal voluntary contraction of the adductor pollicis muscle, sustained for 60 seconds; however it was not determined whether the reduced firing frequency was restricted to the fast twitch motor units (Bigland-Ritchie, Jones and Woods, 1979). However, studies of the discharge properties of single fast twitch motor units in the short extensor of the big toe and the anterior tibial muscle on maximal voluntary effort (Grimby et al, 1981) revealed that their rates rapidly declined, and after a few seconds they failed to respond tonically. At the same time, slow twitch units decreased slowly in firing rate and continued to fire rhythmically for several minutes. Nevertheless, Bigland-Ritchie et al (1982; 1982a) recently provided evidence that a reduction of motorneuron firing rates during a sustained maximal voluntary contraction of the adductor pollicis muscle did not cause the observed force loss. The force of voluntary contraction could not be increased by supramaximal stimulation of the ulnar nerve; a finding that was accounted for by a threefold slowing of relaxation rate, which facilitated a high degree of tetanic fusion despite the reduction in motorneuron discharge rate. Finally, it has recently been suggested by Di Prampero et al (1981) that a reduction in contractile speed rather than depletion of high energy phosphates may be a major cause of fatigue during activities requiring maximal power output.

This study has demonstrated that cycling activity of less than 10 s duration should be performed at pedalling speeds approaching 140 rpm in order to achieve the greatest rate of doing work. For efforts of longer duration (< 30 s) the optimal speed is approximately 100 rpm, whereas for the successful maintenance of power over longer periods of time the most economical rate is 60 rpm, or perhaps even less (Hill, 1922; Dickinson, 1929). These results are in accordance with the observation that many racing cyclists choose to pedal at crank velocities above 110 rpm in their endeavour to attain maximal power output (Wilkie, 1960). However, even champion racing cyclists who trained for years at high pedalling rates were reported to be most efficient when cycling at 60 rpm (Jordan and Merrill, 1979).

4.4.5 Summary

The total work generated by human leg muscles was measured during 30 seconds of maximal cycling exercise performed at constant pedalling speeds of 60, 100 and 140 rpm respectively. Increases in crank velocity were associated with both a significantly higher intial power output, and a greater rate and extent of decline in power. The changing pattern of power output resulted in a greater production of external work early in the test at the faster pedalling speeds, but less in the later stages. However, the total work generated in 30 s was not significantly different at the various crank velocities. The mean average power for the entire test was slightly less than one horsepower, in good agreement with other studies of maximal work performance.

The significantly greater decline in power at higher rates of isokinetic movement could be attributed to many factors, including a decreased mechanical efficiency; an increased energy metabolism and concomitant accumulation of metabolic products; a selective drop-out and fatigue of fast twitch muscle fibres; a decrease in contractile velocity.

5. GENERAL SUMMARY

5.1 Introduction

This chapter will provide a brief review of the thesis, outline some of the questions raised in the course of the studies and make recommendations concerning possible future research.

5.2 Observations and Conclusions of the Thesis

This thesis has applied classical concepts of muscle testing to the study of maximal power output of human muscles. An isokinetic ergometer (CVE) was developed, and allowed the measurement of in vivo torque-velocity relationships during maximal cycling exercise. In addition, the effects of pedal crank velocity on the external work, power output and fatigue of human leg muscles during 30 seconds of maximal cycling were assessed.

As discussed by Wilkie (1960) most techniques applied to measure the maximal short-term power output of human muscles involve phases of acceleration, in which the load is not appropriately matched to the muscles so as to take full advantage of their characteristic force-velocity relationship. In order to overcome such a limitation it was a major purpose of this thesis to develop a mechanical system based on cycling, capable of quantifying the maximal work output of the legs over as wide a range of pedalling speeds as possible. This objective was realised by coupling an electrical speed controller to a three horsepower DC motor, an arrangement which restricted the pedal crank velocity to a predetermined upper level despite maximal muscular effort by the subject. Forces applied to the pedal cranks were detected by matched pairs of resistance strain gauges located midway along the trailing and leading edges of each crank. The signals from the gauges were transmitted via a brass slip ring, Wheatstone bridge system to strain gauge amplifiers, and subsequently formed a visual output trace on a chart recorder. A static calibration of the system was achieved by suspending various weights from each pedal in turn, and the responses were linear and reproducible from day-to-day.

Throughout this thesis the constant velocity ergometer was used to assess both intra and inter-individual variation in performance at a variety of pedalling speeds and during tests of different duration. In every study the measurements of work, power and fatigue were reproducible in a given individual, although there were the anticipated wide inter-subject differences. Analysis revealed that the measures of peak instantaneous power were highly correlated with the average values derived by integrating the area under the force record; thus results describing either aspect of power may be employed to characterise performance. It is concluded that the constant velocity ergometer is a sensitive, reliable instrument for measuring maximal work performance, and has certain advantages over other available systems. First, the pedalling speed may be maintained constant (over a greater range) up to approximately 93% of the voluntary limit, thereby allowing the measurement of maximal power output over a very wide range. Second, cycling movements are easily co-ordinated in most normal subjects, and allow sufficient time for the generation of true maximal power output before either the depletion of metabolic substrate or the accumulation of metabolic products limits performance. Finally, the method of force recording is sensitive and allows the precise measurement of maximum torque, work and power for each pedal cycle; when the values for successive pedal cycles are plotted as a function of time, fatigue may also be quantified.

In the first major study presented in this thesis the maximal peak torque generated by human leg muscles was measured at a series of pedal crank velocities representing approximately 81 percent of the functional range. The resulting torque-velocity relationship was linear in all subjects; a finding which is at variance with results obtained in isolated, electrically stimulated muscle, but compatible with many other studies of in vivo torque-velocity behaviour which demonstrated a predominantly linear characteristic over all but the slowest velocities. There was a positive relationship between the volume of supposedly active muscle and maximal peak torque output, but it was not sufficient to account for the large inter-individual variation in performance.

Maximal instantaneous power output was a parabolic function of crank velocity, with the maxima occurring from approximately 120 to 160 rpm. The data indicated that maximal power was generated when P/Po was in the range of 0.3 to 0.4, in agreement with classical studies of isolated muscles. Absolute levels of maximal instantaneous power apear to be higher than previously reported, and correspond closely to the theoretical limit for any practicable movement (Wilkie, 1960). The diversity in crank velocity for the generation of maximal power could not be attributed to differences in thigh muscle volume; results from two subjects representative of the extremes of power output at fast crank velocities indicated that variation in muscle fibre type may be one possible factor which contributed to the inconsistency.

The final study was designed to yield more complete information on the ability of muscles to engage in short-term maximal exercise. Torque, work and power were measured throughout 30 s of maximal isokinetic cycling exercise at crank velocities of 60, 100 and 140 rpm respectively. One purpose of the study was to test the hypothesis that the reduction in force during repeated maximal contractions would be greater as a function of speed of movement. The hypothesis was accepted; increases in crank velocity were associated with both a higher initial power output and a significantly greater rate and extent of decline in power. Consequently, more external work was achieved early in the test at the faster pedalling speeds, but less in the later stages; total work during the 30 s however, was similar, irrespective of pedalling speed. The underlying cause(s) of the significantly greater decline in power which accompanied faster speeds of movement could not be identified, and may be related to many factors associated with either energy metabolism or reduced motor unit activation.

5.3 Questions for Further Research

The advantages of the CVE as a system for measuring maximal power output of human muscles were detailed in the previous section. One major advantage over other currently available isokinetic systems is that performance can be quantified over approximately 85 percent of the functional range. Unfortunately, measurements cannot be made at either very slow speeds or the highest speeds. However, it should be possible to overcome this limitation, and thus enable testing to take place over the entire physiological range. The sprocket assembly attached to the motor reducer drive shaft could be modified to include an additional sprocket with a complement of 40 teeth. The concomitant gearing ratio would facilitate cycling up to at least 180 rpm, corresponding to the highest voluntary speed that has been observed during unloaded conditions (Wilkie, 1960). Testing at slow speeds is prevented by the inability of the pedal cranks to withstand the accompanying large forces. It should be possible to manufacture a set of cranks (from a metal with appropriate stress-strain characteristics) able to absorb higher forces, and yet pliable enough to maintain a sensitive output from the strain gauges. If both these modifications were implemented a torque-velocity characteristic could be derived which theoretically would be more comparable with the results obtained in isolated muscles. Certainly it would yield the most complete data available on the nature of muscles' torque-velocity relationship in vivo.

Studies of maximal knee extensions on the Cybex apparatus have indicated that a greater proportion of Type II fibres in the exercising muscles is associated with an increased capacity to generate power at fast speeds (Thorstensson, Grimby and Karlsson, 1976) but a reduced fatigue resistance (Thorstensson and Karlsson, 1976). These data are in accordance with the properties of isolated muscles (Faulkner, Jones, Round and Edwards, 1980; Moulds, Young, Jones and Edwards, 1977) and receive partial support from this thesis. The individual who generated the maximal peak instantaneous power at fast speeds in the study of torque-velocity relations possessed a predominance of Type II fibres in the exercising muscle, whereas in a subject representative of the other extreme in power output only 53 percent of the fibres were Type II. If there is a distinct functional role for the two fibre types in terms of power output capacity and fatigue resistance, then it should be easier to detect with the present system than the Cybex. The fastest (reliable) angular velocity that can be obtained using the Cybex apparatus is equivalent to only 30 rpm, hardly sufficient to identify functional differences related to high speeds of movement. Studies to answer this question would require subjects with known, and markedly different populations of fibre types.

The cause(s) of the greater rate and exent of decline in power observed during 30 s of cycling at the faster crank velocities could be investigated using the needle biopsy technique (Bergstrom, 1962). A large number of subjects would be needed for the study, willing to donate samples of muscle tissue after various brief periods of exercise at different pedalling speeds. Detailed biochemical analysis would reveal whether there was an increased rate of energy turnover at the fast speeds, potentially responsible for the significantly greater fatigue.

The sensitivity of the CVE and the repeatability of the test in a given individual establish it as an excellent instrument for examining muscular performance during maximal exercise. There are several studies concerned with the underlying causes of fatigue in which repeated tests in a given individual are essential. For example, the hydrogen ion has been implicated as a major potential cause of fatigue during brief periods of activity requiring maximal power (Hermansen, 1981); it would be possible with the CVE to test the hypothesis that an induced metabolic acidosis would impair performance during short-term exercise, as has already been demonstrated in long-term, heavy work (Jones, Sutton, Taylor and Toews, 1979).

In the previous chapter it was suggested that the contribution of different fibre types to whole muscle tension may have varied during cycling at fast and slow pedalling rates. The significant inverse correlation between each individual's $\dot{V}O_2$ max and fatigue index at 60 rpm suggested a greater contribution by Type I fibres. On the other hand, the greater initial power output and fatigue incurred during cycling at the higher speeds suggested an increased contribution to performance by Type II fibres. Certain approaches might help to clarify the situation. First, if Type I fibres are more heavily involved at 60 rpm then the breathing of a hyperoxic mixture might be expected to improve perform ance, but not at 140 rpm. Second, an exercise and diet regimen which depleted muscle glycogen may seriously inhibit performance at 140 but not 60 rpm. Finally, during several repeated 30 s maximal bouts of pedalling, the glycogen depletion should be much greater in the Type II fibres following exercise at 140 rpm than 60 rpm, although the total work should be similar. However, it is acknowledged that caution is advised in the interpretation of experiments utilising glycogen depletion as an indicator of muscle fibre type recruitment (Burke, 1981).

Edwards (1977; 1980) has discussed the usefulness of measures of voluntary muscle strength (particularly the quadriceps) in the clinical assessment of patients with various neuromuscular disorders. However, reliable measures of maximal isometric tension may be difficult to achieve in many patients, due to the discomfort involved. The CVE offers an additional method for quantifying the short-term muscular performance of those patients who are able to co-ordinate bicycling movements. The data obtained might be more indicative of their ability to cope with the demands imposed by daily living, in which dynamic contractions predominate.

Progressive exercise tests have been used extensively to investigate patients with cardiorespiratory disorders (Jones and Campbell, 1981), and it is not uncommon to witness situations in which the limiting factor is unclear. The CVE offers an ideal opportunity to measure the maximum work that can be performed by the leg muscles during a brief period, in which deficits in central circulatory function should not impair performance. Such a test could prove a powerful adjunct to conventional exercise procedures in the diagnosis and management of patients with cardiorespiratory disease.

Appendix 1

TORQUE-VELOCITY AND POWER-VELOCITY RELATIONSHIPS IN SPRINTERS AND LONG DISTANCE RUNNERS

In the study of torque-velocity and power-velocity relationships reported in chapter 3 it was suggested that a high proportion of Type II fibres in the exercising muscles may be one factor contributing to a greater power output at fast pedalling speeds. There are several reports that sprinters possess a greater proportion of Type II fibres than long distance runners (Thorstensson, 1976; Gregor et al, 1979). Because of these results, measurements were obtained in 3 elite male sprinters and 3 elite long distance runners of peak torque generated at six pedal crank velocities. The results indicated that the sprinters were considerably more powerful than the distance runners, particularly at pedalling rates above 100 rpm (Fig. 36). It seems possible that these differences may be attributed, at least in part, to a greater proportion of Type II fibres in the leg muscles of the sprinters.

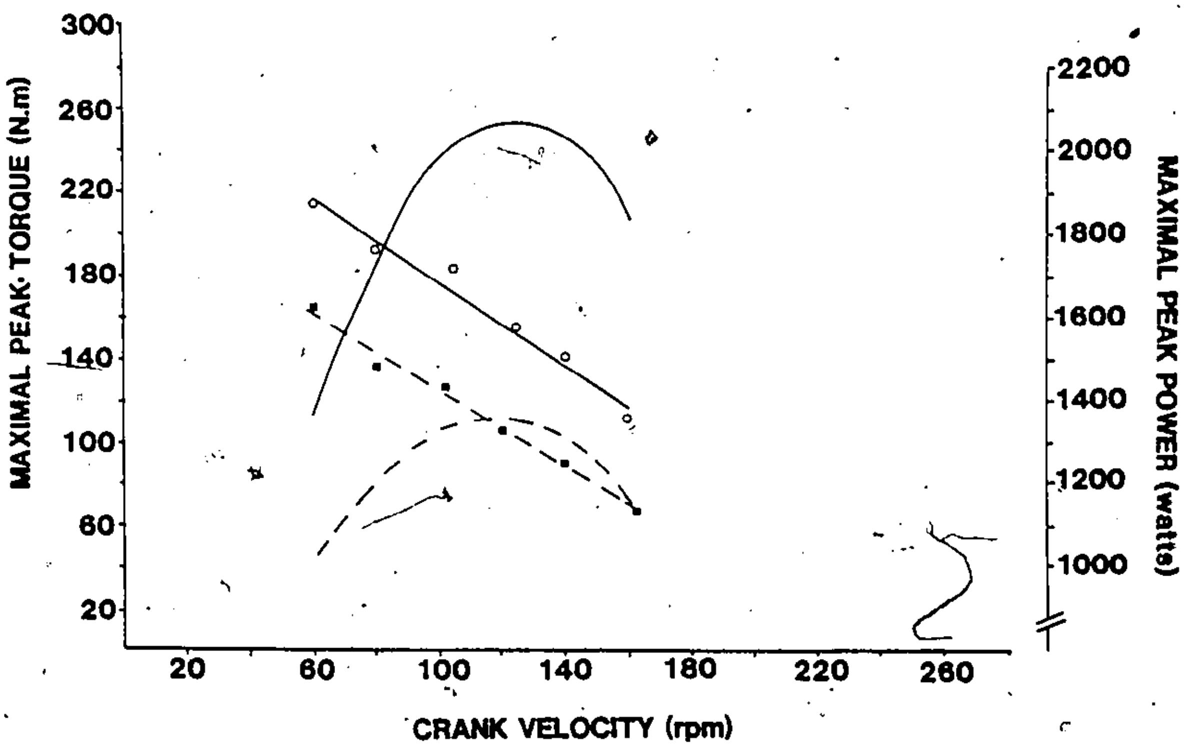


Figure 36. The linear torque-velocity relationship and parabolic power-velocity curve in 3 young male sprinters ——— and 3 long distance runners ------. Error bars are omitted for the sake of clarity.

Appendix 2

CALCULATION OF THIGH MUSCLE VOLUME

In the study of torque-velocity relationships the volume of muscle and bone between the gluteal fold and knee joint space (both legs) was determined for each subject by two independent methods (Table 4).

The first method was an anthropometric technique for partitioning the volume of the thigh into three segments which are similar to truncated cones (Jones and Pearson, 1969). With the subject standing upright and the feet slightly apart the height above the floor and the circumference were measured at four sites. Skin-fold thicknesses were measured with a Harpenden fat caliper from the anterior and posterior thigh in the mid line at the one third subischial height level. The double layer of skin-fold tissue recorded by the calipers was converted to a single measurement using a regression equation calculated from a comparison between X-ray fat and caliper fat (Jones and Pearson, 1969) (Table 2). An estimate of the muscle plus bone volume was derived by subtracting the corrected fat caliper recording from the cone diameters and calculating the inner truncated cone volume from the formula $1/3\ h(a + \sqrt{(ab)} + b)$, where h is height, a and b are the areas of two parallel surfaces calculated from circumference measurements.

In the second procedure the volume of the thigh between the same anatomical sites was determined for each subject from soft tissue X-rays obtained by computed tomography (CAT) (Hounsfield, 1973) (Fig. 37; 38). The distance between the knee joint space and gluteal fold was measured, and nine evenly spaced tomographic pictures were taken (Ohio Nuclear 2020 scanner). The cross-sectional area of the total thigh, muscle and bone respectively, was measured in each picture using a graphics analyser (Numonics, model 1239). A program for stepped section volume was used to calculate the total volume of each component. Using this technique it was readily apparent that extramuscular fat thickness was not constant along the length of the thigh, and there was substantial inter-subject variation in the extent of intramuscular fat (Fig. 37; 38). It was concluded that the measures of thigh muscle volume obtained by CAT were more discriminating than those derived by anthropometry. Consequently, the values of torque and power when adjusted for thigh muscle volume determined by CAT were considered to be more appropriate than when standardized according to anthropometric measurements.

Table 2. (Table provided courtesy of Dr. A. J. Sargeant)

LINEAR REGRESSION EQUATIONS ($y = a + bx$) RELATING FOUR UNCOMPRESSED ROENTGENOGRAMMETRIC VALUES (y) TO EQUIVALENT SKINFOLD CALIPER MEASUREMENTS (x)

SUBCUTANEOUS FAT SITE	SEX	AGE RANGE YRS	REGRESSION EQUATION	COEFFICIENT OF VARIATION, %	CORRELATION
Anterior Thigh	M	18 - 40	$y = 1.01419 + 0.55696x$	± 13.63	0.93
	F	18 - 28	$y = 4.08859 + 0.40689x$	± 12.91	0.83
	M	6 - 15	$y = 0.37963 + 0.59371x$	± 14.60	0.96
	F	6 - 15	$y = 0.27118 + 0.49610x$	± 6.98	0.98
Posterior Thigh	M	18 - 40	$y = 1.36874 + 0.53231x$	± 19.00	0.90
	F	18 - 28	$y = -9.40519 + 0.99236x$	± 26.95	0.77
	M	6 - 15	$y = 0.28403 + 0.54534x$	± 8.06	0.98
	F	6 - 15	$y = 0.07780 + 0.52600x$	± 6.75	0.98
Medial Calf	M	18 - 40	$y = 0.98517 + 0.49945x$	± 17.40	0.87
	F	18 - 28	$y = 1.27296 + 0.47684x$	± 13.60	0.89
	M	6 - 15	$y = 0.48261 + 0.50738x$	± 20.77	0.85
	F	6 - 15	$y = 0.56786 + 0.50593x$	± 15.91	0.94
Lateral Calf	M	18 - 40	$y = 0.87011 + 0.39259x$	± 17.82	0.82
	F	18 - 28	$y = 2.09455 + 0.33943x$	± 12.96	0.80
	M	6 - 15	$y = 1.11566 + 0.43311x$	± 17.74	0.82
	F	6 - 15	$y = 1.77205 + 0.38433x$	± 16.70	0.83

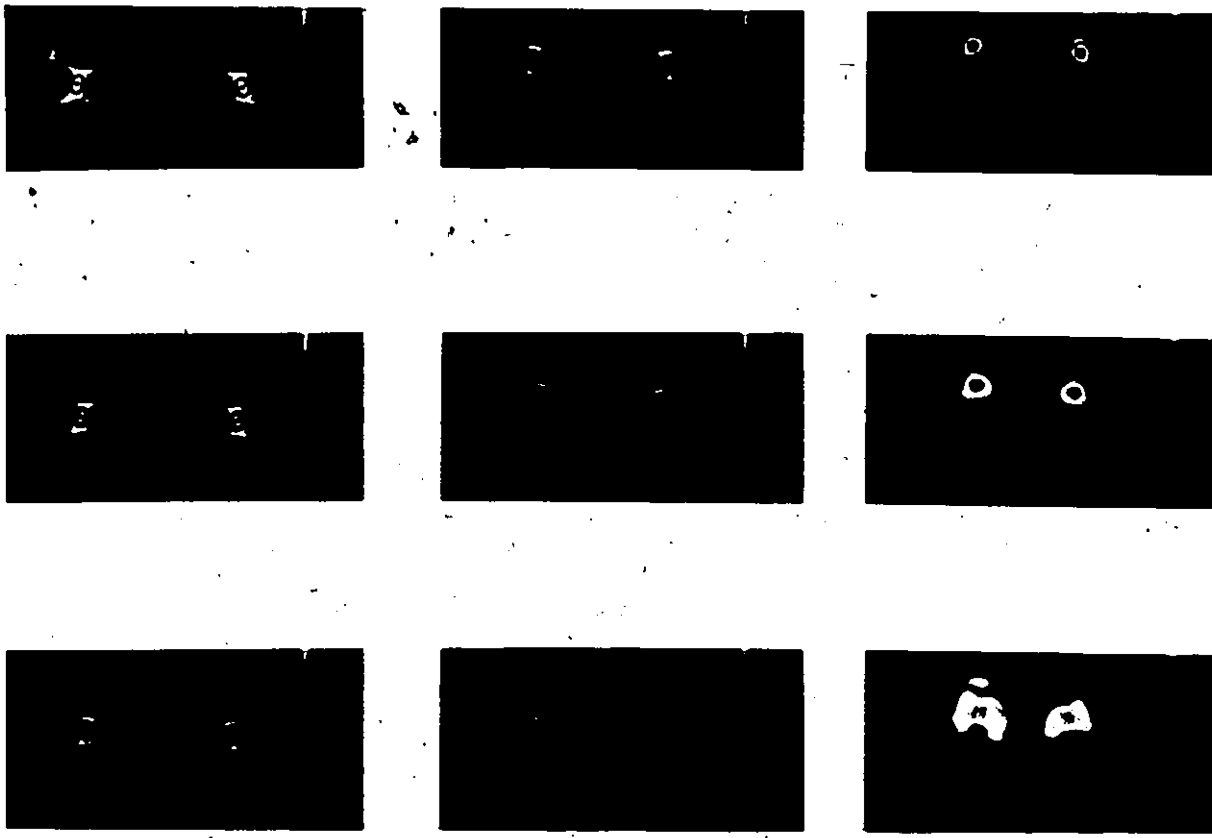


Figure 37. NMR computerized tomographic pictures of both thighs in a [illegible] subject. Both intramuscular and extra-muscular fat [illegible] clearly visible as darker areas. The pictures should be read vertically downwards starting at the left, e.g. the top left picture was taken at the level of the gluteal fold, whereas the picture at the bottom of the right column coincides with the knee joint space.

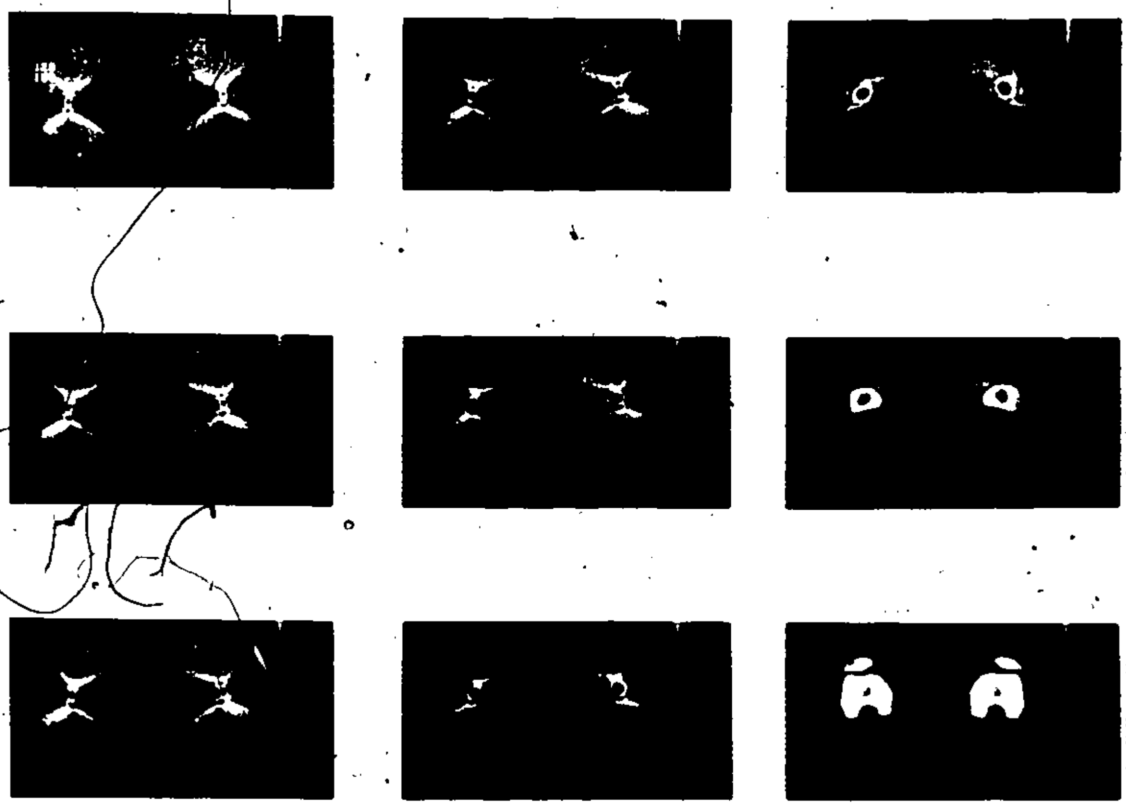


Figure 38. Nine computerized tomographic pictures of both thighs in a subject with much more fat content.

Appendix 3

RELATIONSHIP BETWEEN AEROBIC CAPACITY AND DECLINE IN PEAK TORQUE DURING 45 S OF CYCLING AT 60 RPM

It was reported in section 4.3.2 that there was a significant inverse relationship in 13 subjects between the fatigue index for peak torque during 30 s of maximal cycling at 60 rpm, and maximal oxygen uptake expressed per kg body weight ($r = -0.63$). A similar correlation was evident in the preliminary studies (section 2.2) of peak torque generated during 45 s of cycling at 60 rpm ($r = -0.84$) (Fig. 39). In that study the variability between subjects was illustrated by a comparison between a young trained power lifter and a marathon runner (Fig. 40). The power lifter generated a greater maximal peak torque, but by 45 s torque had declined by 48.6 per cent. In contrast the marathoner produced a lower maximal peak torque but fatigued more slowly, declining by only 29.4 per cent.

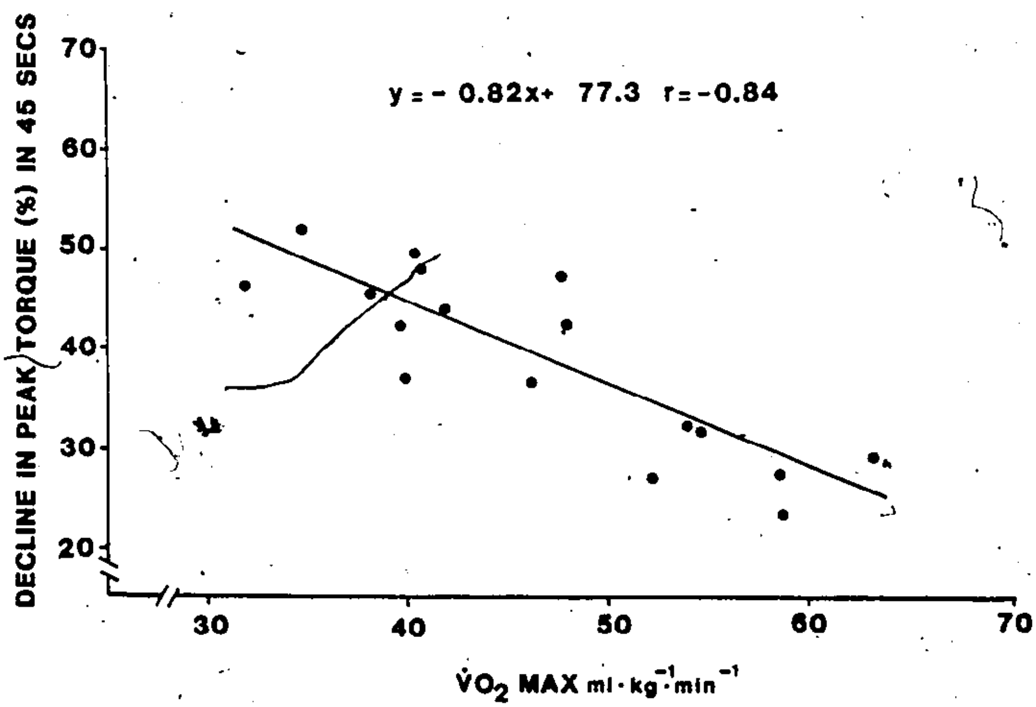


Figure 39. Relationship obtained in 17 subjects between decline in peak torque during 45 s of maximal cycling at 60 rpm and maximal oxygen uptake expressed per kg body weight

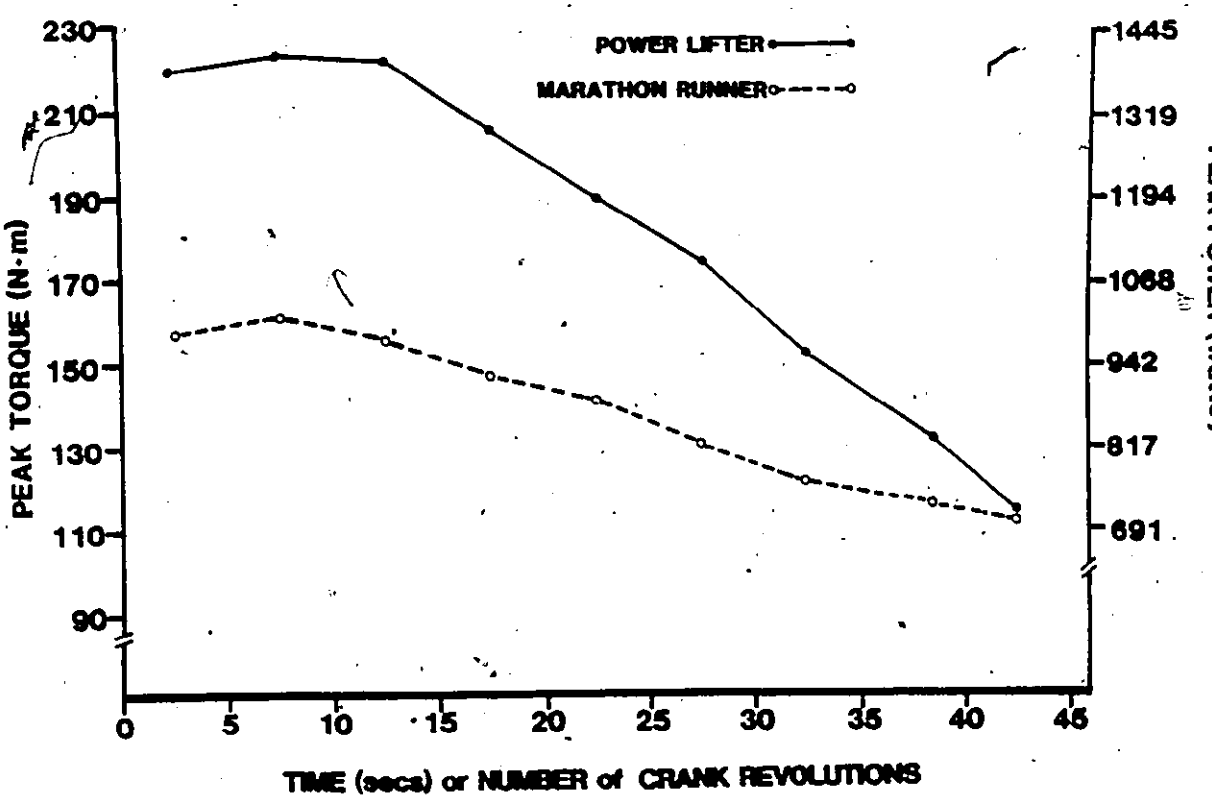


Figure 40. Peak torque during 45 s of maximal effort in a marathon runner and a power lifter.

Appendix 4

PLASMA LACTATE CONCENTRATION AFTER 30 S OF CYCLING AT 60 AND 140 RPM

In section 4.3.5 it was reported that the plasma lactate concentrations measured three minutes after 30 s of maximal cycling at 60, 100 and 140 rpm were almost identical in the three conditions (Table 1). This suggested a similar rate of glycolysis and/or efflux of lactate from muscle, despite the significantly greater initial power output, rate and extent of fatigue observed at the faster pedalling speeds. In a subsequent study of five subjects who performed 30 s of maximal cycling at 60 and 140 rpm, blood samples were drawn at rest, immediately post-exercise and at two minute intervals for ten minutes. The results indicated similar plasma lactate concentrations in the early stages of recovery, but between 4 to 10 minutes the lactate concentrations were significantly higher following performance at 140 rpm (Fig. 41).

The differences in plasma lactate concentrations immediately following exercise are probably indicative of the rates of lactate efflux from muscle, whereas the steady-state levels probably reflect more the lactate production that occurred during exercise. If one makes the assumption that lactate was uniformly distributed in total body water and no lactate removal from this pool occurred in the first eight minutes after exercise the calculated lactate production during pedalling at 140 rpm (621 m moles) was approximately 44.8% higher than at 60 rpm (429 m moles). This variation may be attributed to differences in lactate production by muscle during the exercise, and is consistent with the hypothesis (section 4.4.4) that pedalling at faster speeds was associated with an increased energy metabolism.

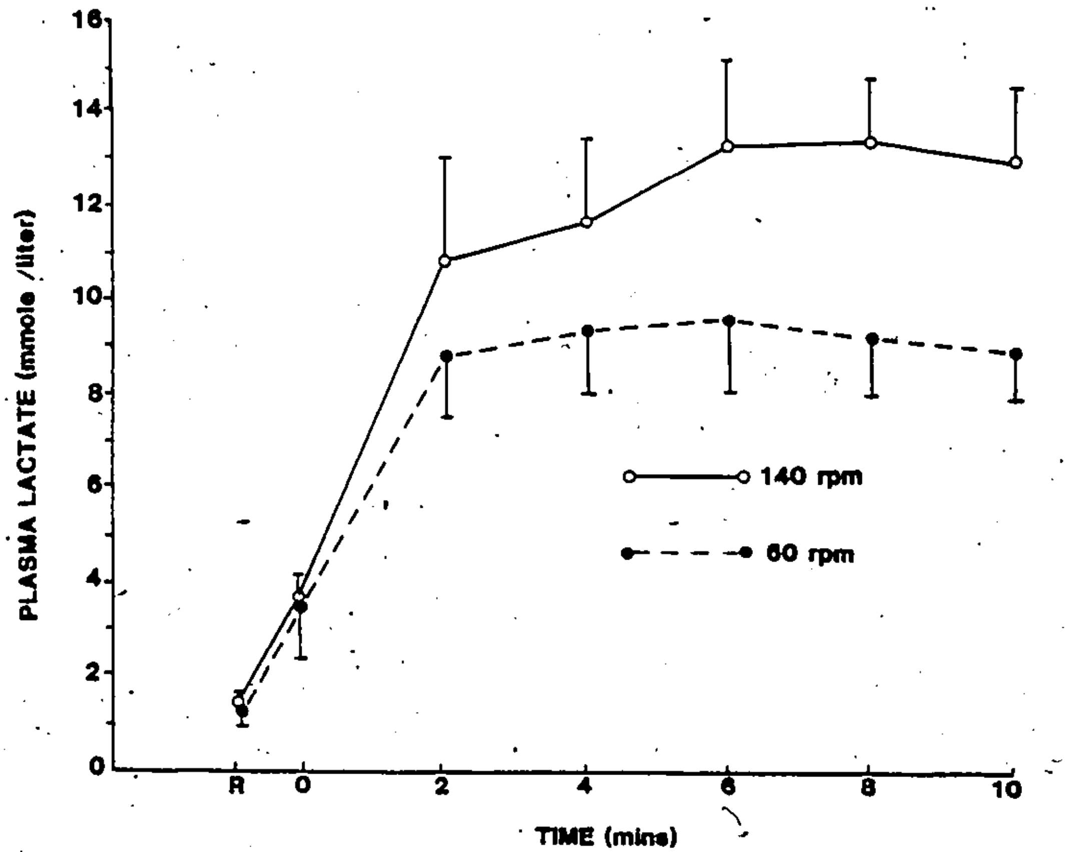


Figure 41. Lactate concentration (mean ±1 S.E.M.) in samples of arterialized venous plasma at rest and following 30 s of maximal cycling at 60 and 140 rpm. Measurements were made in 5 healthy young male subjects. The values obtained between 4 and 10 mins were significantly higher ($p<0.05$) following exercise at 140 rpm.

Appendix 5

CONSENT FORM

The purpose of this study is to investigate the effects of crank velocity on the ability to generate external mechanical power during brief bouts of maximal intensity cycling exercise. The study involves three parts:

1. Approximately 10 secs of cycling at speeds of 20, 40, 60, 80, 100, 120, 140 and 160 rpm, respectively; the entire procedure to be repeated on another day.

2. Maximal intensity cycling for 30 secs at 60 rpm, 100 rpm, and 140 rpm. Tests will be separated by at least one day. One test, selected at random, will be repeated on another day.

3. Before and after the 30 sec tests small quantities of blood will be sampled from a superficial vein in the dorsal surface of the forearm; an indwelling catheter will be used for this purpose and will be placed by a practising physician.

This study is for research purposes only and will be of no direct benefit to me. All information about me will be considered confidential, but the results of the study may be published in a scientific journal.

I understand that I may withdraw from this project at any time, even after signing this consent form, without prejudice.

____

DATE NAME SIGNATURE

____

DATE NAME OF WITNESS SIGNATURE OF WITNESS

Appendix 6

ON-LINE COMPUTER ANALYSIS OF STRAIN-GAUGE SIGNALS

In the studies included in the main body of this thesis which report measurements of work, and average power, the method of calculation was based on manual planimetry of the force record from chart paper. The raw data and appropriate calibration factors were then entered into a computer, which performed the calculations for each pedal cycle. During the course of development the method of force recording progressed until eventually, the voltage output from the strain gauge amplifiers was sampled directly by the computer at either ten or twenty millisecond intervals. The following 13 pages provide an example of a computer printout describing the results of a 30 s test at 60 rpm. The time elapsed during each revolution, and the calculated angular velocity of the pedal cranks is displayed on the first page. Despite the maximal efforts of the subject the time occupied in a single revolution never varied by more than 20 milliseconds (49 to 50 x 20 msec intervals).

****

****

3220.9651 1016.0650 -0.0616

517.2100 2288.9951 0.0767

****

STROKE	START OF STROKE	END OF STROKE	DELTA	RPM
1	44	93	49	61.2
2	93	142	49	61.2
3	142	191	49	61.2
4	191	240	49	61.2
5	240	289	49	61.2
6	289	338	49	61.2
7	338	387	49	61.2
8	387	436	49	61.2
9	436	485	49	61.2
10	485	534	49	61.2
11	534	584	50	60.0
12	584	633	49	61.2
13	633	682	49	61.2
14	682	731	49	61.2
15	731	780	49	61.2
16	780	830	50	60.0
17	830	879	49	61.2
18	879	928	49	61.2
19	928	977	49	61.2
20	977	1026	49	61.2
21	1026	1075	49	61.2
22	1075	1125	50	60.0
23	1125	1174	49	61.2
24	1174	1223	49	61.2
25	1223	1272	49	61.2
26	1272	1322	50	60.0
27	1322	1371	49	61.2
28	1371	1420	49	61.2
29	1420	1470	50	60.0
30	1470	1519	49	61.2

AVERAGE DELTA = 49 AVERAGE RPM = 61.0

****

DY1:PP60.DAT

LEFT PEDAL

****

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK
1	186.0	60.8	59.6	1192.4	389.8	382.0	382.0
2	186.7	63.0	61.7	1196.7	403.9	395.8	777.7
3	198.4	64.7	63.4	1272.2	414.6	406.3	1184.1
4	198.4	64.2	62.9	1271.8	411.7	403.5	1587.6
5	187.5	63.4	62.2	1202.2	406.7	398.5	1986.1
6	187.6	62.8	61.5	1202.6	402.5	394.5	2380.6
7	185.1	60.3	59.1	1186.4	386.6	378.8	2759.4
8	190.0	62.2	60.9	1218.0	398.7	390.7	3150.1
9	192.0	63.2	61.9	1231.1	404.9	396.8	3546.9
10	192.4	64.4	63.1	1233.8	412.9	404.6	3951.5
11	187.5	61.2	61.2	1178.2	384.2	384.2	4335.7
12	184.4	59.8	58.6	1182.5	383.4	375.7	4711.5
13	196.2	63.2	61.9	1257.9	405.2	397.1	5108.6
14	186.2	60.7	59.5	1193.6	389.0	381.2	5489.9
15	188.6	60.8	59.6	1209.0	389.7	381.9	5871.7
16	182.9	61.2	61.2	1149.2	384.7	384.7	6256.5
17	184.4	61.2	60.0	1182.5	392.5	384.6	6641.1
18	174.9	60.2	59.0	1121.3	386.3	378.6	7019.7
19	188.1	61.6	60.4	1205.8	395.1	387.2	7406.9
20	176.6	59.5	58.3	1131.9	381.5	373.9	7780.8
21	185.9	63.9	62.6	1192.0	409.7	401.5	8182.3
22	175.0	60.6	60.6	1099.6	380.5	380.5	8562.7
23	178.5	59.0	57.8	1144.6	378.1	370.5	8933.3
24	180.2	63.3	62.0	1155.6	405.8	397.7	9331.0
25	174.1	59.8	58.6	1116.5	383.5	375.9	9706.8
26	170.4	56.4	56.4	1070.6	354.3	354.3	10061.2
27	172.9	58.3	57.1	1108.6	373.5	366.0	10427.2
28	169.5	56.3	55.2	1086.5	360.8	353.6	10780.8
29	168.6	56.1	56.1	1059.4	352.7	352.7	11133.5
30	163.4	56.4	55.2	1047.8	361.3	354.1	11487.6

DY1:PP60.DAT

LEFT PEDAL

**** - ****
SUMMARY FOR THE ABOVE DATA
**** ****

MAXIMUM VALUES DURING RUN
****

MAX. PEAK TORQUE =	198.4 NEWTON-METERS	ON PEDAL STROKE #	3
MAX. AVG. TORQUE =	64.7 NEWTON-METERS	ON PEDAL STROKE #	3
MAX. PEAK POWER =	1272.2 WATTS	ON PEDAL STROKE #	3
MAX. AVG. POWER =	414.6 WATTS	ON PEDAL STROKE #	3
MAX. WORK =	406.3 JOULES	ON PEDAL STROKE #	3

FATIQUE INDEXES (FI)
****

PEAK TORQUE FI(%)=	17.6	DECAY FACTOR=	1.27 (NEWTON-METERS/SECOND)
PEAK POWER FI(%)=	17.6	DECAY FACTOR=	8.15 (WATTS/SECOND)
AVG. POWER FI(%)=	12.9	DECAY FACTOR=	1.94 (WATTS/SECOND)

DY1:PP60.DAT

LEFT PEDAL

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK

THE ABOVE VALUES SMOOTHED BY MOVING AVERAGE

1	186.0	60.8	59.6	1192.4	389.8	382.0	382.0
2	190.4	62.8	61.6	1220.4	402.8	394.7	776.7
3	194.5	64.0	62.7	1246.9	410.1	401.9	1178.5
4	194.8	64.1	62.8	1248.7	411.0	402.8	1581.3
5	191.2	63.5	62.2	1225.6	407.0	398.8	1980.1
6	186.7	62.2	60.9	1197.1	398.6	390.6	2370.8
7	187.5	61.8	60.5	1202.4	395.9	388.0	2758.8
8	189.0	61.9	60.6	1211.9	396.7	388.8	3147.5
9	191.5	63.2	62.0	1227.7	405.5	397.4	3544.9
10	190.7	62.9	62.1	1214.4	400.7	395.2	3940.1
11	188.1	61.8	61.0	1198.2	393.5	388.2	4328.3
12	189.4	61.4	60.6	1206.2	391.0	385.7	4714.0
13	188.9	61.2	60.0	1211.3	392.6	384.7	5098.7
14	190.3	61.6	60.3	1220.2	394.6	386.7	5485.5
15	185.9	60.9	60.1	1183.9	387.8	382.6	5868.1
16	185.3	61.1	60.3	1180.2	[illegible]	383.7	6251.8
17	180.7	60.9	60.1	1151.0	387.8	382.6	6634.5
18	182.5	61.0	59.8	1169.9	391.3	383.5	7017.9
19	179.8	60.5	59.3	1153.0	387.6	379.9	7397.8
20	183.5	61.7	60.4	1176.6	395.4	387.5	7785.4
21	179.2	61.3	60.5	1141.2	390.6	385.3	8170.7
22	179.8	61.1	60.3	1145.4	389.4	384.2	8554.8
23	177.9	60.9	60.1	1133.3	388.1	382.9	8937.7
24	177.6	60.7	59.5	1138.9	389.2	381.4	9319.1
25	174.9	59.8	59.0	1114.3	381.2	376.0	9695.0
26	172.5	58.2	57.4	1098.6	370.5	365.4	10060.5
27	170.9	57.0	56.2	1088.6	362.9	358.0	10418.4
28	170.3	56.9	56.1	1084.8	362.3	357.4	10775.9
29	167.2	56.3	55.5	1064.6	358.3	353.5	11129.4
30	163.4	56.4	55.2	1047.8	361.3	354.1	11483.5

DY1:PP60.DAT

LEFT PEDAL

**** SUMMARY FOR THE ABOVE DATA ****

MAXIMUM VALUES DURING RUN

MAX. PEAK TORQUE =	194.8 NEWTON-METERS	ON PEDAL STROKE #	4
MAX. AVG. TORQUE =	64.1 NEWTON-METERS	ON PEDAL STROKE #	4
MAX. PEAK POWER =	1248.7 WATTS	ON PEDAL STROKE #	4
MAX. AVG. POWER =	411.0 WATTS	ON PEDAL STROKE #	4
MAX. WORK =	402.8 JOULES	ON PEDAL STROKE #	4

FATIGUE INDEXES (FI)

PEAK TORQUE FI(%)= 16.1	DECAY FACTOR=	1.18	(NEWTON-METERS/SECOND)
PEAK POWER FI(%)= 16.1	DECAY FACTOR=	7.56	(WATTS/SECOND)
AVG. POWER FI(%)= 12.1	DECAY FACTOR=	1.87	(WATTS/SECOND)

DY1: PP60. DAT

RIGHT PEDAL

****

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK
1	190.6	60.6	59.4	1221.8	388.4	380.6	380.6
2	199.8	62.4	61.1	1280.8	399.9	391.9	772.5
3	203.7	62.0	60.7	1305.8	397.4	389.5	1162.0
4	201.6	62.3	61.1	1292.6	399.4	391.5	1553.5
5	202.0	62.8	61.5	1295.0	402.4	394.4	1947.8
6	177.8	56.4	55.3	1139.7	361.7	354.5	2302.3
7	198.5	62.2	60.9	1272.4	398.7	390.7	2693.0
8	194.5	60.3	59.1	1246.9	386.5	378.8	3071.8
9	202.5	62.5	61.2	1298.5	400.7	392.7	3464.5
10	197.2	62.0	60.8	1264.1	397.5	389.5	3854.0
11	187.7	57.8	57.8	1179.1	363.1	363.1	4217.0
12	187.2	58.9	57.8	1200.2	378.0	370.4	4587.4
13	190.6	59.2	58.0	1221.8	379.4	371.9	4959.3
14	183.3	56.1	55.0	1175.1	359.5	352.3	5311.6
15	184.0	55.9	54.7	1179.5	358.1	351.0	5662.6
16	195.1	60.3	60.3	1225.8	378.6	378.6	6041.2
17	177.2	57.1	55.9	1136.3	366.0	358.7	6399.9
18	188.8	58.7	57.5	1210.5	376.2	368.7	6768.5
19	194.4	58.8	57.7	1246.4	377.3	369.7	7138.3
20	196.9	58.9	57.8	1262.1	377.8	370.3	7508.5
21	189.2	61.7	60.5	1212.9	395.5	387.6	7896.1
22	182.1	57.4	57.4	1144.4	360.8	360.8	8257.0
23	189.0	61.7	60.5	1211.5	395.8	387.9	8644.9
24	186.2	60.5	59.3	1193.8	387.9	380.1	9025.0
25	185.2	59.6	58.4	1187.4	382.3	374.6	9399.6
26	181.4	56.5	56.5	1140.0	354.7	354.7	9754.3
27	185.4	60.1	58.9	1188.4	385.2	377.5	10131.8
28	170.8	54.8	53.7	1095.0	351.1	344.0	10475.9
29	177.8	54.3	54.3	1116.9	341.4	341.4	10817.3
30	183.1	56.1	55.0	1173.6	359.9	352.7	11170.0

DY1:PP60.DAT

RIGHT PEDAL

SUMMARY FOR THE ABOVE DATA

MAXIMUM VALUES DURING RUN

MAX. PEAK TORQUE	= 203.7 NEWTON-METERS	ON PEDAL STROKE #	3
MAX. AVG. TORQUE	= 62.8 NEWTON-METERS	ON PEDAL STROKE #	5
MAX. PEAK POWER	= 1305.8 WATTS	ON PEDAL STROKE #	3
MAX. AVG. POWER	= 402.4 WATTS	ON PEDAL STROKE #	5
MAX. WORK	= 394.4 JOULES	ON PEDAL STROKE #	5

FATIGUE INDEXES (FI)

PEAK TORQUE FI(%)= 10.1	DECAY FACTOR=	0.75 (NEWTON-METERS/SECOND)
PEAK POWER FI(%)= 10.1	DECAY FACTOR=	4.80 (WATTS/SECOND)
AVG. POWER FI(%)= 10.6	DECAY FACTOR=	1.66 (WATTS/SECOND)

DY1:PP60.DAT

RIGHT PEDAL

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK
	THE ABOVE VALUES SMOOTHED BY MOVING AVERAGE						
1	190.6	60.6	59.4	1221.8	388.4	380.6	380.6
2	198.0	61.6	60.4	1269.5	395.2	387.3	768.0
3	201.7	62.2	61.0	1293.1	398.9	390.9	1158.9
4	202.4	62.4	61.1	1297.8	399.8	391.8	1550.7
5	193.8	60.5	59.3	1242.4	387.9	380.1	1930.8
6	192.7	60.5	59.2	1235.7	387.6	379.8	2310.6
7	190.2	59.6	58.4	1219.7	382.3	374.7	2685.3
8	198.5	61.7	60.4	1272.6	395.3	387.4	3072.7
9	198.1	61.6	60.4	1269.8	394.9	387.0	3459.7
10	195.8	60.8	59.9	1247.2	387.1	381.8	3841.4
11	190.7	59.6	58.8	1214.4	379.5	374.3	4215.7
12	188.5	58.6	57.9	1200.3	373.5	368.4	4584.2
13	187.0	58.1	56.9	1199.0	372.3	364.9	4949.0
14	185.9	57.0	55.9	1192.1	365.7	358.4	5307.4
15	187.4	57.4	56.7	1193.5	365.4	360.6	5668.1
16	185.4	57.7	57.0	1180.5	367.6	362.8	6030.8
17	187.0	58.7	57.9	1190.8	373.6	368.6	6399.5
18	186.8	58.2	57.0	1197.7	373.1	365.7	6765.2
19	193.4	58.8	57.6	1239.6	377.1	369.6	7134.7
20	193.5	59.8	58.6	1240.5	383.5	375.9	7510.6
21	189.4	59.3	58.5	1206.5	378.1	372.9	7883.5
22	186.8	60.3	59.5	1189.6	384.1	378.8	8262.2
23	185.8	59.9	59.1	1183.2	381.5	376.3	8638.5
24	186.8	60.6	59.4	1197.5	388.7	380.9	9019.4
25	184.3	58.9	58.1	1173.7	375.0	369.8	9389.2
26	184.0	58.7	57.9	1171.9	374.1	369.0	9758.2
27	179.2	57.1	56.3	1141.1	363.7	358.8	10116.9
28	178.0	56.4	55.6	1133.4	359.2	354.3	10471.3
29	177.2	55.1	54.3	1128.5	350.8	346.1	10817.3
30	183.1	56.1	55.0	1173.6	359.9	352.7	11170.0

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DY1:PP60.DAT

                              RIGHT PEDAL
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                        ****                       ****
                          SUMMARY FOR THE ABOVE DATA
                        ****                       ****
--------------------------------------------------------------------------------

                          MAXIMUM VALUES DURING RUN
                        *****************************

   MAX. PEAK TORQUE =  202.4 NEWTON-METERS     ON PEDAL STROKE #    4
   MAX. AVG. TORQUE =   62.4 NEWTON-METERS     ON PEDAL STROKE #    4
   MAX. PEAK POWER  = 1297.8 WATTS             ON PEDAL STROKE #    4
   MAX. AVG. POWER  =  399.8 WATTS             ON PEDAL STROKE #    4
   MAX. WORK        =  391.8 JOULES            ON PEDAL STROKE #    4

                          FATIGUE INDEXES ( FI )
                        *****************************

 PEAK TORQUE FI(%)=  9.6   DECAY FACTOR=   0.73 (NEWTON-METERS/SECOND)
 PEAK POWER  FI(%)=  9.6   DECAY FACTOR=   4.68 (WATTS/SECOND)
 AVG. POWER  FI(%)= 10.0   DECAY FACTOR=   1.50 (WATTS/SECOND)

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DY1: PP60. DAT

BOTH PEDALS AVERAGED
****

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK
1	188.3	121.4	118.9	1207.1	778.2	762.6	762.6
2	193.2	125.4	122.9	1238.7	803.7	787.7	1550.3
3	201.0	126.7	124.1	1289.0	812.1	795.8	2346.1
4	200.0	126.5	124.0	1282.2	811.2	794.9	3141.0
5	194.8	126.2	123.7	1248.6	809.1	792.9	3933.9
6	182.7	119.2	116.8	1171.2	764.2	748.9	4682.9
7	191.8	122.5	120.0	1229.4	785.3	769.6	5452.4
8	192.2	122.5	120.0	1232.5	785.2	769.5	6221.9
9	197.3	125.6	123.1	1264.8	805.6	789.5	7011.4
10	194.8	126.4	123.9	1249.0	810.4	794.1	7805.5
11	187.6	118.9	118.9	1178.6	747.3	747.3	8552.8
12	185.8	118.8	116.4	1191.3	761.4	746.1	9298.9
13	193.4	122.4	119.9	1239.9	784.7	769.0	10067.9
14	184.7	116.7	114.4	1184.3	748.5	733.6	10801.5
15	186.3	116.6	114.3	1194.2	747.8	732.8	11534.3
16	189.0	121.5	121.5	1187.5	763.3	763.3	12297.7
17	180.8	118.3	115.9	1159.4	758.5	743.3	13041.0
18	181.8	118.9	116.5	1165.9	762.5	747.2	13788.2
19	191.2	120.5	118.1	1226.1	772.4	757.0	14545.1
20	186.7	118.4	116.1	1197.0	759.4	744.2	15289.3
21	187.5	125.6	123.1	1202.5	805.2	789.1	16078.4
22	178.6	118.0	118.0	1122.0	741.3	741.3	16819.7
23	183.7	120.7	118.3	1178.0	773.9	758.5	17578.1
24	183.2	123.8	121.3	1174.7	793.7	777.8	18355.9
25	179.7	119.4	117.1	1152.0	765.8	750.5	19106.4
26	175.9	112.8	112.8	1105.3	709.1	709.1	19815.5
27	179.1	118.3	116.0	1148.0	758.7	743.5	20559.0
28	170.1	111.0	108.8	1090.8	711.9	697.6	21256.7
29	173.2	110.5	110.5	1088.0	694.1	694.1	21950.8
30	173.2	112.5	110.2	1110.7	721.2	706.8	22657.6

DY1:PP60.DAT

BOTH PEDALS AVERAGED

****   ****
SUMMARY FOR THE ABOVE DATA
****   ****

MAXIMUM VALUES DURING RUN
****

MAX. PEAK TORQUE	= 201.0	NEWTON-METERS	ON PEDAL STROKE # 3
MAX. AVG. TORQUE	= 126.7	NEWTON-METERS	ON PEDAL STROKE # 3
MAX. PEAK POWER	= 1289.0	WATTS	ON PEDAL STROKE # 3
MAX. AVG. POWER	= 812.1	WATTS	ON PEDAL STROKE # 3
MAX. WORK	= 795.8	JOULES	ON PEDAL STROKE # 3

FATIGUE INDEXES (FI)
****

PEAK TORQUE	FI(%)= 13.8	DECAY FACTOR=	1.01 (NEWTON-METERS/SECOND)
PEAK POWER	FI(%)= 13.8	DECAY FACTOR=	6.47 (WATTS/SECOND)
AVG. POWER	FI(%)= 11.2	DECAY FACTOR=	3.30 (WATTS/SECOND)

DY1: PP60. DAT

BOTH PEDALS AVERAGED

STROKE #	MAXIMUM TORQUE	AVERAGE TORQUE	IMPULSE	PEAK POWER	AVERAGE POWER	WORK	CUMULATIVE WORK

THE ABOVE VALUES SMOOTHED BY MOVING AVERAGE

1	188.3	121.4	118.9	1207.1	778.2	762.6	762.6
2	194.2	124.5	122.0	1244.9	798.0	782.0	1544.6
3	198.1	126.2	123.7	1270.0	809.0	792.8	2337.4
4	198.6	126.5	123.9	1273.3	810.8	794.6	3132.0
5	192.5	124.0	121.5	1234.0	794.8	778.9	3910.9
6	189.7	122.6	120.2	1216.4	786.2	770.5	4681.4
7	188.9	121.4	119.0	1211.0	778.2	762.6	5444.0
8	193.8	123.5	121.1	1242.2	792.0	776.2	6220.2
9	194.8	124.8	122.3	1248.7	800.4	784.4	7004.6
10	193.2	123.7	122.0	1230.8	787.7	777.0	7781.5
11	189.4	121.4	119.7	1206.3	773.0	762.5	8544.1
12	188.9	120.0	118.4	1203.3	764.4	754.1	9298.2
13	188.0	119.3	116.9	1205.2	764.9	749.6	10047.8
14	188.1	118.6	116.2	1206.1	760.3	745.1	10792.9
15	186.7	118.3	116.7	1188.7	753.2	743.2	11536.2
16	185.4	118.8	117.2	1180.4	756.5	746.5	12282.7
17	183.9	119.6	118.0	1170.9	761.4	751.3	13033.9
18	184.6	119.2	116.8	1183.8	764.4	749.2	13783.1
19	186.6	119.3	116.9	1196.3	764.7	749.4	14532.5
20	188.5	121.5	119.1	1208.5	779.0	763.4	15295.9
21	184.3	120.7	119.0	1173.8	768.6	758.2	16054.1
22	183.3	121.4	119.8	1167.5	773.5	762.9	16817.1
23	181.8	120.8	119.2	1158.2	769.6	759.2	17576.2
24	182.2	121.3	118.9	1168.2	777.8	762.3	18338.5
25	179.6	118.7	117.1	1144.0	756.2	745.8	19084.3
26	178.2	116.9	115.3	1135.3	744.5	734.4	19818.6
27	175.1	114.1	112.5	1114.9	726.5	716.7	20535.4
28	174.1	113.3	111.8	1109.1	721.6	711.8	21247.2
29	172.2	111.3	109.8	1096.5	709.1	699.5	21946.7
30	173.2	112.5	110.2	1110.7	721.2	706.8	22653.5

DY1:PP60.DAT

BOTH PEDALS AVERAGED

**** SUMMARY FOR THE ABOVE DATA ****

MAXIMUM VALUES DURING RUN
****

MAX. PEAK TORQUE =	198.6 NEWTON-METERS	ON PEDAL STROKE #	4
MAX. AVG. TORQUE =	126.5 NEWTON-METERS	ON PEDAL STROKE #	4
MAX. PEAK POWER =	1273.3 WATTS	ON PEDAL STROKE #	4
MAX. AVG. POWER =	810.8 WATTS	ON PEDAL STROKE #	4
MAX. WORK =	794.6 JOULES	ON PEDAL STROKE #	4

FATIGUE INDEXES (FI)
****

PEAK TORQUE FI(%)= 12.8	DECAY FACTOR=	0.95	(NEWTON-METERS/SECOND)
PEAK POWER FI(%)= 12.8	DECAY FACTOR=	6.12	(WATTS/SECOND)
AVG. POWER FI(%)= 11.0	DECAY FACTOR=	3.37	(WATTS/SECOND)

Appendix 7

SUBJECT DESCRIPTIVE DETAILS AND INDIVIDUAL RESULTS

Values of torque are listed for each leg separately, whereas in general the power output data are representative of both legs. Torque is calculated as N.m, power as watts and work as kilojoules.

Table 3.

DESCRIPTIVE DETAILS OF 17 SUBJECTS WHO PARTICIPATED IN THE INITIAL STUDY OF PEAK TORQUE DURING 45 SECS OF MAXIMAL CYCLING AT 60 RPM

ID	Age (yrs)	Height (cm)	Weight (kgs)	$\dot{V}O_2$ max $ml.kg^{-1}.min^{-1}$
A	33	177.8	70.0	58.4
B	33	181.3	66.0	58.6
C	28	184.5	81.5	47.9
D	34	175.0	75.0	39.9
E	27	180.8	73.0	39.5
F	24	176.8	82.0	47.5
G	31	179.1	76.5	46.0
H	35	176.9	65.0	63.0
I	33	185.9	74.5	41.6
J	33	179.0	69.0	34.7
K	29	173.6	72.6	52.3
L	22	178.5	70.0	40.3
M	36	187.0	89.0	54.5
N	22	178.0	80.0	54.4
O	23	180.6	75.5	31.8
P	32	185.0	84.0	40.6
Q	38	180.2	79.5	38.2
$\bar{x}$	30.2	180.0	75.5	46.4
±SD	5.1	3.8	6.6	9.1

TABLE 4

SUBJECT DESCRIPTIVE DETAILS. SUBJECTS 1 TO 12 PARTICIPATED IN THE STUDY OF TORQUE-VELOCITY RELATIONSHIPS DURING CYCLING; ALL 13 SUBJECTS PARTICIPATED IN THE STUDY OF TORQUE, WORK AND POWER DURING 30 SECS OF MAXIMAL EFFORT AT 60, 100 AND 140 RPM

Name	Age (yrs)	Height (cm)	Weight (kgs)	$\dot{V}O_2$ max $ml \cdot kg^{-1} \cdot min^{-1}$	Anthropometric measure of thigh muscle + bone volume (litres) Right	Left	Mean	C.A.T. measure of thigh muscle + bone volume (litres) Right	Left	Mean	C.A.T. measure of thigh muscle volume (litres) Right	Left	Mean
1. BQ	19	184.3	80.5	49.4	5.10	4.99	5.05	4.23	4.35	4.29	3.91	4.05	3.98
2. HB	22	182.1	87.0	37.2	5.85	5.44	5.64	4.75	4.84	4.80	4.37	4.47	4.42
3. MS	22	173.3	98.5	37.4	6.54	6.72	6.63	4.39	4.86	4.63	4.04	4.48	4.26
4. MH	20	178.1	72.5	46.0	4.29	4.43	4.36	3.94	4.13	4.04	3.62	3.84	3.73
5. GL	21	190	87.5	48.3	5.80	5.82	5.81	4.79	4.92	4.86	4.48	4.59	4.54
6. JG	22	183.8	89.0	36.0	5.56	5.39	5.48	5.62	5.94	5.78	5.20	5.49	5.35
7. AH	19	177.1	69.5	50.8	3.88	4.02	3.95	4.52	5.03	4.78	4.12	4.64	4.38
8. BL	19	185.6	82.5	43.5	5.27	5.18	5.23	4.63	5.03	4.83	4.29	4.67	4.48
9. JP	23	174.6	74.5	49.7	4.15	4.26	4.21	4.03	4.13	4.08	3.80	3.89	3.85
10. GH	22	168.5	64.3	48.2	3.71	3.41	3.56	4.28	4.53	4.41	3.99	4.22	4.11
11. CK	21	169	73.5	44.0	4.50	4.34	4.42	4.35	4.81	4.58	4.04	4.47	4.26
12. TM	22	176	95.0	31.7	4.34	4.45	4.40	-	-	-	-	-	-
13. SM	22	177.3	75.5	42.7	5.17	4.98	5.08	3.73	3.93	3.83	3.43	3.62	3.53
$\bar{x}$	21.1	178.4	80.8	43.5	4.93	4.88	4.91	4.44	4.71	4.58	4.11	4.37	4.24
±SD	1.4	6.5	10.2	6.1	0.92	0.86	0.86	0.49	0.54	0.51	0.46	0.50	0.47

Table 5.

PEAK TORQUE (N·m) AND FATIGUE INDEX DURING A 45 SECOND TEST @ 60 RPM ($\bar{x}$ OF FIVE PEDAL CYCLES)

ID	RIGHT LEG 1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	Fatigue Index	LEFT LEG 1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	Fatigue Index
	Pedal Cycle Number																			
A	154	157	150	143	138	137	132	121	116	26.1	139	142	140	134	125	117	113	105	97	31.7
B	108	113	96	103	101	92	90	90	84	25.7	117	122	115	119	116	106	100	97	95	22.1
C	173	178	179	164	152	144	132	121	108	39.7	166	169	162	152	138	126	113	104	92	45.6
D	166	165	164	151	150	124	116	112	109	34.3	172	171	166	155	148	127	113	107	104	39.5
E	132	127	123	116	105	99	91	84	72	45.5	174	185	179	172	158	147	133	131	107	42.2
F	222	232	233	220	206	187	165	142	124	46.8	219	217	212	195	175	163	141	124	107	51.1
G	165	159	151	141	129	127	121	112	107	35.2	158	151	140	129	121	113	109	106	97	38.6
H	163	168	161	147	142	131	123	119	115	31.5	151	155	152	148	142	130	121	115	113	27.1
I	183	189	176	168	153	136	130	111	104	45.0	172	168	163	153	140	127	119	106	98	43.0
J	155	145	139	132	124	109	103	96	84	45.8	149	135	125	118	108	104	93	91	63	57.7
K	137	129	124	123	120	113	107	101	95	30.7	153	147	149	147	145	138	128	120	119	22.2
L	155	152	142	128	116	107	95	81	76	51.0	158	140	132	125	117	112	105	93	81	48.7
M	195	175	171	176	162	155	150	144	135	30.8	169	161	153	154	141	134	130	123	116	31.4
N	182	187	186	167	154	142	133	124	119	36.4	184	189	190	177	164	162	148	146	136	28.4
O	178	165	153	135	134	128	116	110	98	44.9	201	193	179	165	161	151	135	121	105	47.8
P	163	176	168	153	141	123	113	99	92	47.7	163	170	166	152	143	129	113	103	87	48.8
Q	172	164	157	148	141	128	121	112	100	41.9	152	154	140	130	112	104	93	84	78	49.4
$\bar{x}$	164.9	163.6	157.2	147.9	139.3	128.4	119.9	110.5	102.2	38.8	164.5	162.9	156.6	148.5	138.5	128.9	118.1	109.8	99.7	39.7
±SD	25.6	27.4	30.1	26.9	24.5	22.4	20.0	17.7	17.2	8.0	23.2	23.9	24.6	21.2	19.6	18.8	16.0	15.2	17.2	10.8

Table 6.

PEAK TORQUE (N·m) AND FATIGUE INDEX (% OF BOTH LEGS) DURING A 45 SECOND TEST @ 60 RPM ($\bar{x}$ OF 5 PEDAL CYCLES)

I.D.	Pedal Cycle Number 1 - 5	6 - 10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	Fatigue Index
A	146.5	149.5	145.0	138.5	131.5	127.0	122.5	113.0	106.5	28.5
B	112.5	117.5	105.5	111.0	108.5	99.0	95.0	93.5	89.5	23.8
C	169.5	173.5	170.5	158.0	145.0	135.0	122.5	112.5	100.0	42.5
D	169.0	168.0	165.0	153.0	149.0	125.5	114.5	109.5	106.5	37.0
E	153.0	156.0	151.0	144.0	131.5	123.0	112.0	102.5	89.5	42.6
F	220.5	224.5	222.5	207.5	190.5	175.0	153.0	133.0	115.5	48.6
G	161.5	155.0	144.5	135.5	125.0	120.0	114.5	109.0	102.0	36.8
H	157.0	161.5	156.5	147.5	142.0	130.5	122.0	117.0	114.0	29.4
I	177.5	178.5	169.5	160.5	146.5	131.5	124.5	108.5	101.0	43.4
J	152.0	140.0	132.0	125.0	116.0	106.5	98.0	93.5	74.5	51.0
K	145.0	138.0	136.5	135.0	132.5	125.5	117.5	110.5	107.0	26.2
L	156.5	144.0	137.0	126.5	116.5	109.5	100.0	87.0	78.5	49.8
M	182.0	168.0	162.0	165.0	151.5	144.5	140.0	133.5	125.5	31.0
N	183.0	188.0	188.0	172.0	159.0	152.0	140.5	135.0	127.5	32.2
O	189.5	179.0	166.0	150.0	147.5	139.5	125.5	115.5	101.5	46.4
P	163.0	173.0	167.0	152.5	142.0	126.0	113.0	101.0	89.5	48.3
Q	162.0	159.0	148.5	139.0	126.5	116.0	107.0	98.0	89.0	45.1
$\bar{X}$	164.7	163.1	156.9	148.3	138.9	128.6	118.9	110.1	101.0	39.0
±SD	23.0	23.8	25.5	21.8	19.3	17.9	15.4	14.1	14.9	9.0

Table 7.

MAXIMAL PEAK TORQUE (N·m) GENERATED BY 12 SUBJECTS (LEFT LEG) DURING BRIEF BOUTS OF MAXIMAL CYCLING AT EITHER 6 or 8 CRANK VELOCITIES, RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

	R. P. M.															
	20		40		60		80		100		120		140		160	
NAME	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2
TM	-	-	303.0	291.0	2152.0	268.8	195.0	216.0	192.0	187.2	169.0	163.2	128.0	151.2	116.4	115.2
AH	229.3	-	229.3	-	183.4	189.2	165.1	180.6	146.7	146.7	128.4	128.4	91.7	86.0	82.5	86.0
JG	238.4	-	240.7	-	188.0	247.6	188.0	220.1	149.0	172.4	144.4	163.2	139.8	150.4	110.0	110.0
BL	220.8	-	193.2	-	230.0	189.2	211.6	225.8	174.8	189.2	169.7	167.7	156.4	146.2	140.3	157.4
MH	262.2	-	230.0	-	202.4	199.0	156.4	172.4	142.6	139.8	136.2	128.4	124.2	118.3	101.2	91.7
HB	340.4	-	248.4	-	220.8	227.9	193.2	174.2	165.6	157.0	165.6	146.2	119.6	129.0	92.0	96.8
CK	211.6	-	207.0	-	174.8	161.7	149.5	137.6	131.1	126.8	126.0	111.8	110.4	90.3	92.0	77.4
MS	276.0	-	269.1	-	211.6	243.0	184.0	191.7	156.4	151.3	138.0	142.1	128.8	114.6	108.1	87.1
GH	-	-	-	-	169.6	146.2	158.2	144.5	132.0	116.1	128.4	111.8	114.6	103.2	96.3	88.6
GL	-	-	-	-	259.1	275.1	234.8	210.9	194.9	176.5	167.4	167.8	155.9	149.0	139.8	126.5
JP	-	-	-	-	224.7	240.3	211.4	204.7	151.3	172.7	146.9	138.0	126.4	133.5	100.1	102.4
BQ	-	-	-	-	209.2	201.7	187.0	183.4	160.2	154.1	149.5	150.4	136.2	136.6	115.7	119.2
$\bar{x}$	254.1	-	240.1	-	210.5	215.8	186.2	188.5	158.1	157.5	147.5	143.3	127.7	125.7	107.9	104.9
±SD	44.3	-	34.6	-	28.6	41.0	25.7	28.6	20.8	23.0	16.8	20.2	18.3	23.2	18.1	22.4

Table 8.

MAXIMAL PEAK TORQUE (N·m) GENERATED BY 12 SUBJECTS (RIGHT LEG) DURING BRIEF BOUTS OF MAXIMAL CYCLING AT EITHER 6 or 8 CRANK VELOCITIES, RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

	R. P. M.															
	20		40		60		80		100		120		140		160	
NAME	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2
TM	-	-	303.3	294.0	241.0	287.8	185.0	210.7	185.0	185.0	154.0	154.2	128.0	133.6	131.5	128.5
AM	245.8	-	216.3	-	189.2	192.7	157.3	169.6	142.5	146.7	137.6	137.6	98.3	105.5	88.5	91.7
JG	245.8	-	226.1	-	201.5	247.6	176.9	209.1	157.3	165.1	152.4	158.2	152.4	146.7	118.0	108.2
BL	226.1	-	197.0	-	221.2	190.7	196.6	201.7	176.9	174.2	167.1	169.6	167.0	133.0	147.5	154.1
MH	260.5	-	235.9	-	206.4	201.7	162.2	169.6	147.5	160.5	137.6	137.6	113.0	113.7	103.2	96.3
HB	349.0	-	285.0	-	234.8	231.5	176.9	206.3	153.3	178.8	187.0	159.6	142.5	146.7	127.8	105.5
CK	202.4	-	207.0	-	165.6	161.3	147.2	137.6	131.1	127.2	123.3	110.1	103.5	99.6	87.4	83.0
MS	294.0	-	249.9	-	213.2	220.1	176.4	178.8	147.0	155.9	137.2	131.1	127.4	117.1	110.3	92.3
GH	-	-	-	-	149.8	155.9	151.7	154.1	123.2	132.0	131.8	122.0	113.8	110.0	94.8	85.3
GL	-	-	-	-	220.1	245.8	201.7	209.1	181.1	181.6	151.3	169.6	139.4	128.4	126.5	119.2
JP	-	-	-	-	235.7	228.3	194.9	200.8	158.2	174.2	146.7	146.7	128.4	123.8	112.3	110.0
BQ	-	-	-	-	233.8	217.2	197.2	178.0	174.2	149.5	155.9	160.2	146.7	153.5	119.2	124.6
$\bar{x}$	260.5	-	240.0	-	209.4	215.1	177.0	185.5	156.4	160.9	148.5	146.4	130.0	126.0	113.9	108.2
±SD	48.2	-	37.4	-	28.8	37.5	18.9	24.4	19.7	19.1	17.1	18.9	20.6	17.4	18.3	20.8

Table 9.

MAXIMAL PEAK TORQUE (N·m) GENERATED BY 12 SUBJECTS (MEAN OF BOTH LEGS) DURING BRIEF BOUTS OF MAXIMAL CYCLING AT EITHER 6 OR 8 CRANK VELOCITIES; RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

	R. P. M.															
	20		40		60		80		100		120		140		160	
NAME	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2
TM	-	-	303.0	292.5	247.0	278.3	190.0	213.4	188.5	186.1	162.0	158.7	128.0	142.4	124.0	121.9
AM	237.5	-	222.8	-	186.3	191.0	161.2	172.4	144.6	146.7	133.0	133.0	95.0	95.8	85.5	88.9
JG	242.1	-	233.4	-	194.8	247.6	182.5	214.6	153.2	168.8	148.4	160.7	146.1	148.1	114.0	109.1
BL	223.5	-	195.1	-	225.6	190.0	204.1	213.8	175.9	181.7	168.4	168.7	161.7	139.6	143.9	155.8
MH	261.4	-	233.0	-	204.4	200.4	159.3	171.0	145.1	150.2	136.9	133.0	118.6	116.0	102.2	94.0
HB	344.7	-	266.9	-	229.6	229.7	185.1	190.3	159.5	167.9	176.3	152.9	131.1	137.9	109.9	101.2
CK	207.0	-	207.0	-	170.2	161.5	148.4	137.6	131.1	127.0	124.7	111.0	107.0	95.0	89.7	80.2
MS	285.0	-	259.5	-	212.4	231.6	180.2	185.3	151.7	153.6	137.6	136.6	128.1	115.9	109.2	89.7
GH	-	-	-	-	159.7	151.1	155.0	149.3	127.6	124.1	130.1	116.9	114.2	106.6	95.6	87.0
GL	-	-	-	-	239.6	260.5	218.3	210.0	188.0	179.1	159.4	168.7	147.7	138.7	133.2	122.9
JP	-	-	-	-	230.2	234.3	203.2	202.8	154.8	173.5	146.8	142.4	127.4	128.7	106.2	106.2
BQ	-	-	-	-	221.5	209.5	192.0	180.7	167.2	151.8	152.7	155.3	141.5	145.1	117.5	121.9
$\bar{x}$	257.3	-	240.1	-	210.1	215.5	181.6	186.8	157.3	159.2	148.0	144.8	128.9	125.9	110.9	106.6
±SD	46.0	-	35.0	-	27.6	38.6	21.8	25.8	19.8	20.4	16.2	19.2	18.7	19.3	17.2	21.4

Table 10.

MAXIMAL PEAK POWER (WATTS) GENERATED BY 12 SUBJECTS (LEFT LEG) DURING BRIEF BOUTS OF MAXIMAL CYCLING @ EITHER 6 OR 8 CRANK VELOCITIES, RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

	R. P. M.															
	20		40		60		80		100		120		140		160	
NAME	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2
TM	-	-	1205.5	1188.2	1556.7	1632.3	1572.1	1786.6	1970.0	1999.2	1893.3	2084.6	1755.6	2058.0	1876.8	1893.6
AM	480.2	-	912.3	-	1094.5	1168.7	1313.7	1456.0	1643.5	1489.9	1586.3	1586.3	1305.7	1224.7	1364.8	1422.7
JG	524.2	-	1033.3	-	1259.8	1451.7	1496.0	1728.3	1669.2	1750.9	1889.8	1965.0	2093.1	2141.6	1819.7	1819.7
BL	531.7	-	829.3	-	1517.0	1149.0	1750.0	1773.0	1958.0	1921.0	2132.0	2107.0	2342.0	2281.0	2438.0	2604.0
MH	604.0	-	1011.4	-	1356.0	1229.3	1310.0	1407.9	1567.8	1463.7	1782.5	1613.2	1820.5	1684.5	1674.1	1517.0
HB	819.7	-	988.3	-	1387.1	1407.8	1557.6	1404.4	1699.2	1643.8	2080.6	1836.9	1753.1	1836.9	1493.0	1601.3
CK	465.2	-	888.6	-	1079.8	998.9	1267.9	1109.3	1345.2	1327.6	1556.7	1404.7	1572.0	1285.8	1483.4	1280.4
MS	606.8	-	1070.6	-	1329.3	1475.6	1502.7	1545.5	1604.8	1536.6	1704.9	1785.3	1793.6	1583.8	1743.0	1440.9
GH	-	-	-	-	1029.9	887.8	1275.4	1134.7	1340.6	1215.6	1613.2	1357.8	1631.8	1469.5	1593.1	1465.7
GL	-	-	-	-	1600.5	1728.2	1991.3	1700.3	2101.8	1848.0	2103.2	2108.2	2219.9	2121.6	2254.1	2092.6
JP	-	-	-	-	1364.5	1484.4	1704.3	1650.3	1536.6	1826.3	1845.7	1733.8	1813.1	1900.9	1655.9	1694.0
BQ	-	-	-	-	1292.3	1309.3	1507.6	1478.6	1727.6	1613.4	1815.7	1889.6	1939.4	1945.1	1914.0	1971.9
$\bar{x}$	576.0	-	992.4	-	1322.3	1326.9	1520.7	1514.6	1680.3	1636.3	1833.7	1789.4	1836.7	1794.4	1775.8	1733.7
±SD	120.6	-	117.9	-	185.5	250.5	218.3	229.1	235.4	241.4	199.0	259.8	284.2	345.8	315.1	369.5

Table 11.

MAXIMAL PEAK POWER (WATTS) GENERATED BY 12 SUBJECTS (RIGHT LEG) DURING BRIEF BOUTS OF MAXIMAL CYCLING @ EITHER 6 OR 8 CRANK VELOCITIES, RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

NAME	R. P. M. 20 DAY 1	20 DAY 2	40 DAY 1	40 DAY 2	60 DAY 1	60 DAY 2	80 DAY 1	80 DAY 2	100 DAY 1	100 DAY 2	120 DAY 1	120 DAY 2	140 DAY 1	140 DAY 2	160 DAY 1	160 DAY 2
TM	-	-	1205.5	1200.5	1488.7	1747.7	1491.5	1942.8	1898.2	1975.7	1725.2	1969.7	1755.6	1818.4	2117.1	2112.3
AM	514.7	-	860.6	-	1129.1	1190.4	1251.7	1367.3	1596.4	1489.9	1700.0	1700.0	1399.7	1502.2	1464.0	1517.0
JG	540.4	-	970.6	-	1350.3	1451.7	1407.7	1642.0	1762.2	1676.7	1994.5	1904.8	2281.7	2088.9	1952.0	1789.9
BL	544.5	-	845.7	-	1459.0	1158.0	1626.0	1584.0	1982.0	1769.0	2099.0	2131.0	2500.3	2074.8	2563.6	2549.2
MH	600.0	-	1037.3	-	1383.0	1246.0	1358.6	1385.1	1621.5	1680.4	1800.8	1728.8	1656.4	1619.0	1707.2	1593.1
HB	840.4	-	1133.9	-	1497.6	1430.0	1426.2	1663.2	1572.9	1866.8	2349.5	2005.2	2088.8	2088.9	2074.0	1745.2
CK	445.0	-	888.6	-	1023.0	996.4	1248.4	1109.3	1345.2	1331.8	1523.3	1383.3	1473.8	1418.2	1409.2	1373.0
MS	646.4	-	994.3	-	1339.3	1336.6	1440.6	1441.5	1508.3	1583.3	1695.1	1647.1	1774.1	1618.4	1778.5	1526.9
GH	-	-	-	-	909.7	946.7	1223.0	1210.1	1251.2	1382.0	1655.9	1481.7	1620.4	1566.3	1568.2	1411.1
GL	-	-	-	-	1359.6	1544.1	1710.6	1685.7	1953.0	1901.4	1900.9	2130.9	1984.9	1828.3	2039.7	1971.9
JP	-	-	-	-	1431.3	1410.3	1571.3	1618.8	1606.7	1842.1	1843.1	1843.1	1841.8	1762.8	1857.7	1819.7
BQ	-	-	-	-	1444.3	1409.9	1589.8	1435.0	1878.6	1565.3	1893.4	2012.8	2088.9	2185.7	1971.9	2061.2
$\bar{X}$	590.2	-	992.1	-	1317.9	1323.3	1445.4	1490.4	1664.7	1672.0	1848.4	1828.2	1872.2	1797.7	1875.3	1789.2
±SD	127.3		129.6	-	192.3	228.0	158.7	199.0	235.4	207.5	222.7	243.4	328.2	260.9	320.9	342.4

Table 12.

MAXIMAL PEAK POWER (WATTS) GENERATED BY 12 SUBJECTS ($\bar{x}$ OF BOTH LEGS) DURING BRIEF BOUTS OF MAXIMAL CYCLING @ EITHER 6 OR 8 CRANK VELOCITIES, RANGING FROM 20 TO 166 RPM, ON TWO SEPARATE DAYS

	R. P. M.															
	20		40		60		80		100		120		140		160	
NAME	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2	DAY 1	DAY 2
TM	-	-	1205.5	1194.7	1522.7	1690.0	1531.8	1764.8	1934.1	1987.5	1809.5	2027.2	1755.6	1938.2	1997.0	2003.0
AM	497.5	-	886.5	-	1111.8	1179.6	1282.7	1411.7	1620.0	1489.9	1643.2	1643.2	1352.7	1363.4	1414.4	1469.9
JG	532.3	-	1002.0	-	1305.1	1451.7	1451.8	1685.2	1715.7	1713.8	1942.2	1934.9	2187.4	2115.3	1885.9	1804.8
BL	538.1	-	837.5	-	1488.0	1153.5	1688.0	1678.5	1970.0	1845.0	2115.5	2119.0	2421.2	2177.9	2500.8	2576.6
MH	602.0	-	1024.4	-	1369.5	1237.7	1334.3	1396.5	1594.6	1572.1	1791.1	1671.0	1738.5	1651.8	1690.7	1555.1
HB	830.1	-	1061.1	-	1442.4	1418.9	1491.9	1533.8	1636.1	1755.3	2215.1	1921.1	1921.0	1962.9	1783.5	1673.3
CK	455.1	-	888.6	-	1051.4	997.7	1258.2	1109.3	1345.2	1329.7	1540.0	1394.0	1522.9	1352.0	1446.3	1326.7
HS	626.6	-	1032.5	-	1334.3	1406.1	1471.7	1493.5	1556.6	1560.0	1700.0	1716.2	1783.9	1601.1	1760.8	1483.9
GH	-	-	-	-	969.8	917.3	1249.2	1172.4	1295.9	1298.8	1634.6	1419.8	1626.1	1517.9	1580.7	1438.4
GL	-	-	-	-	1480.1	1636.2	1851.0	1693.0	2027.4	1874.7	2002.1	2119.6	2102.4	1975.0	2146.9	2032.3
JP	-	-	-	-	1427.9	1447.4	1637.8	1634.6	1571.7	1834.2	1844.4	1788.5	1827.5	1831.9	1756.8	1756.9
BQ	-	-	-	-	1368.3	1359.6	1548.7	1456.8	1803.1	1589.4	1854.5	1951.2	2014.2	2065.4	1943.0	2016.6
$\bar{x}$	583.1	-	992.3	-	1322.6	1324.6	1483.1	1502.5	1672.5	1654.2	1841.1	1808.8	1854.5	1796.1	1825.6	1761.5
±SD	123.5	-	118.8	-	182.1	235.3	185.1	207.4	230.5	217.6	201.7	246.4	296.4	289.5	302.7	352.8

Table 13.

PEAK TORQUE AND FATIGUE INDEX DURING A 30 SECOND TEST AT 60 RPM ($\bar{X}$ OF THREE PEDAL CYCLES)

NAME	Right Leg											Left Leg											
	Pedal Cycle Number																						
	1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	Fatigue Index	1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	Fatigue Index	RPM
BQ	208.8	201.1	192.6	181.0	183.4	184.0	173.3	171.8	160.2	160.1	23.3	185.5	197.5	199.6	199.3	190.1	184.6	177.6	179.7	165.7	165.7	17.0	55
HS	197.5	182.2	164.4	170.6	174.2	170.0	161.1	158.3	146.7	146.7	25.7	207.9	196.2	184.9	186.5	189.8	183.1	177.0	166.6	152.8	154.1	25.9	56
JG	208.2	235.7	233.2	227.2	222.2	208.8	205.4	178.8	162.6	159.6	32.3	200.2	220.7	221.0	207.2	207.5	194.1	187.1	178.5	167.8	150.4	31.9	56
JG	181.6	202.8	196.8	197.4	195.2	187.0	182.4	163.9	135.2	135.3	33.3	169.3	177.3	184.3	177.3	178.8	173.9	168.1	167.8	155.0	155.0	15.9	58
HS	193.9	202.5	198.0	189.2	182.8	180.9	174.6	168.6	162.3	161.3	20.3	200.2	206.6	195.9	192.6	183.4	177.3	172.7	172.7	152.8	142.1	31.2	55
SM	188.3	196.8	192.6	184.0	178.5	176.1	159.6	150.7	138.8	133.0	32.4	195.3	205.4	205.7	199.6	201.1	196.8	184.3	181.3	163.8	157.7	23.3	57
SM	180.0	210.9	207.2	207.5	211.2	196.2	175.5	167.2	150.7	141.7	32.9	203.9	216.1	200.8	208.8	203.0	184.6	165.4	160.2	151.0	149.9	30.6	58
GL	211.9	217.6	214.8	218.3	213.5	203.7	202.8	199.6	197.7	184.1	15.7	236.6	221.6	217.0	221.6	210.9	215.2	210.6	205.7	194.1	192.6	18.6	58
AM	161.7	188.3	177.3	171.2	165.1	164.4	157.4	151.3	155.3	146.3	22.3	164.4	176.1	165.1	179.1	177.6	165.7	169.0	161.7	158.3	154.1	14.0	57
JP	169.6	183.4	173.9	175.1	179.1	169.6	165.7	159.9	152.2	145.8	20.5	175.5	176.1	173.6	171.8	185.6	178.5	162.3	149.8	146.1	133.9	27.9	56
HB	214.9	214.9	175.5	179.1	192.3	171.2	170.0	175.5	172.7	146.7	31.7	191.7	193.5	166.3	148.9	175.8	170.6	163.8	152.8	158.3	157.7	18.5	58
BL	147.0	155.3	137.9	148.6	134.8	134.8	125.6	118.9	136.6	128[illegible]	17.3	154.1	158.3	166.3	159.3	147.0	144.3	138.5	138.5	147.0	134.3	19.2	58
MH	191.3	180.6	189.2	185.7	171.8	162.6	147.9	143.7	148.6	148.5	22.4	184.3	184.3	171.2	173.6	176.4	171.8	163.2	155.6	140.3	143.1	22.4	55
TH	216.4	193.8	234.1	225.0	219.2	205.4	207.5	180.6	162.9	155.0	33.8	200.8	188.0	209.4	216.4	208.2	194.7	192.0	172.7	159.3	151.3	30.1	58
CK	148.9	160.8	159.3	155.3	155.6	148.2	140.3	134.5	131.1	129.3	19.6	140.3	153.4	155.6	150.1	152.5	148.9	139.1	131.1	126.5	133.0	14.5	56
$\bar{X}$	188.0	195.1	189.8	187.7	185.3	177.5	170.0	161.6	154.2	148.1	25.6	187.3	191.4	187.8	186.2	185.8	178.9	171.4	165.0	155.9	151.7	22.7	56.7
±SD	23.0	21.2	26.4	23.6	24.4	21.0	23.4	20.0	17.0	14.6	6.5	24.0	20.9	20.8	23.0	19.1	18.2	18.6	18.5	14.9	14.9	6.4	1.2

Table 14.

PEAK TORQUE AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST AT 60 RPM ($\bar{x}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	Fatigue Index
BQ	197.2	199.3	195.7	190.3	186.8	184.3	175.5	175.8	162.9	162.9	18.3
MS	202.7	189.2	174.7	178.5	182.0	176.5	169.0	162.5	149.8	150.4	25.8
MS	197.1	204.5	197.0	190.9	183.1	179.1	173.7	170.7	157.6	151.7	25.8
JG	204.2	228.2	227.1	217.5	214.9	201.4	196.2	178.7	165.2	155.0	32.1
JG	175.5	190.0	190.5	187.5	187.0	180.4	175.5	165.8	145.1	145.2	23.8
SM	191.8	201.1	199.1	191.8	189.8	186.5	171.9	166.0	151.3	145.7	27.7
SM	192.0	213.5	204.0	208.2	207.1	190.4	170.4	163.7	150.8	145.8	31.7
GL	224.3	219.6	215.9	219.9	212.2	209.5	206.7	202.7	195.9	188.3	16.0
AM	163.1	182.2	171.2	175.1	171.3	165.1	163.2	156.5	156.8	150.2	17.6
JP	172.5	179.9	173.8	173.5	182.4	174.1	164.0	154.8	149.2	139.8	23.4
HB	203.3	204.2	170.9	164.0	184.0	170.9	166.9	164.1	165.5	152.2	25.5
BL	150.5	156.8	152.1	153.9	140.9	139.5	132.0	128.7	141.8	131.4	16.2
MH	187.8	187.8	175.9	181.4	181.0	171.8	162.9	151.8	142.0	145.8	22.4
TM	208.6	190.9	221.8	220.7	213.7	200.1	199.8	176.7	161.1	153.1	31.0
CK	144.6	157.1	157.4	152.7	154.1	148.6	139.7	132.8	128.8	131.1	16.7
$\bar{x}$	187.7	193.6	188.5	186.0	186.0	178.5	171.2	153.4	154.9	149.9	23.6
±SD	22.3	20.1	22.8	20.8	20.8	18.7	19.8	18.1	15.2	13.5	5.7

Table 15.

PEAK POWER AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST @ 60 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	16 - 18	19 - 21	22 - 24	25 - 27	28 - 30	Fatigue Index
BQ	1135.2	1147.7	1128.3	1095.7	1075.5	1061.4	1010.3	1012.1	938.2	938.2	18.3
MS	1134.8	1177.9	1134.3	1099.1	1054.5	1031.4	1000.0	982.7	907.3	873.8	25.8
MS	1188.2	1109.4	1024.2	1046.6	1067.2	1035.0	991.1	952.5	878.2	881.8	25.8
JG	1065.5	1154.0	1157.1	1137.6	1135.6	1095.7	1065.6	1007.1	881.2	881.2	23.8
JG	1197.2	1337.9	1331.6	1275.1	1259.9	1181.0	1150.6	1047.5	968.7	908.6	32.1
SH	1165.7	1296.5	1239.0	1264.1	1257.6	1156.4	1034.8	994.0	916.0	885.4	31.7
SH	1144.7	1200.3	1188.5	1144.7	1132.8	1112.8	1026.1	990.5	903.0	867.4	27.7
GL	1361.9	1333.7	1311.1	1335.6	1288.7	1271.9	1255.1	1230.7	1189.6	1143.7	16.0
AM	973.2	1087.2	1021.5	1045.3	1022.5	985.1	974.1	934.0	935.8	896.1	17.6
JP	1011.7	1053.8	1018.9	1017.1	1069.4	1020.6	961.5	907.7	874.6	819.7	23.4
HB	1234.4	1239.9	1037.6	995.8	1117.4	1037.6	1013.5	996.8	1005.1	924.4	25.5
BL	914.2	952.2	923.5	934.6	855.7	847.4	801.9	781.5	861.3	797.7	16.2
MH	1081.6	1081.6	1013.0	1044.7	1042.5	989.2	938.2	873.9	817.6	839.6	22.4
TH	1266.9	1159.2	1346.7	1340.2	1297.5	1214.9	1213.0	1072.9	978.2	930.0	31.0
CK	847.7	921.2	923.0	895.2	903.3	871.0	819.0	778.7	755.4	768.8	16.7
$\bar{x}$	1114.9	1150.2	1119.8	1111.4	1105.3	1060.8	1017.0	970.8	920.6	890.4	23.6
±SD	136.5	123.3	140.9	138.4	130.8	117.1	123.4	112.3	97.5	85.1	5.7

Table 16.

AVERAGE POWER AND FATIGUE INDEX (SUM OF BOTH LEGS) DURING A 30 SECOND TEST @ 60 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	16 - 18	19 - 21	22 - 24	25 - 27	28 - 30	Fatigue Index
BQ	778.2	783.6	771.1	750.6	743.3	754.3	709.1	712.8	617.0	617.0	21.3
MS	682.3	704.4	660.3	686.7	657.5	616.9	616.1	591.7	575.2	545.2	22.6
MS	677.6	637.2	605.2	602.2	647.7	605.2	595.0	539.2	513.8	512.7	24.3
JG	702.8	744.8	708.3	697.6	688.1	687.5	654.0	635.0	543.3	543.3	27.1
JG	696.7	789.0	767.0	748.0	707.6	666.0	644.6	574.7	534.0	529.5	32.9
SM	767.3	806.3	777.6	728.7	740.1	699.1	642.2	652.4	631.5	639.4	20.7
SM	755.8	802.9	800.2	768.6	764.2	763.8	709.0	669.8	636.7	615.7	23.3
GL	1017.2	998.3	984.6	996.3	904.2	880.3	844.4	845.7	791.9	796.0	21.7
AM	639.7	744.0	676.2	703.2	690.6	628.0	626.8	598.5	580.3	527.3	29.2
JP	637.7	643.5	634.0	637.0	637.7	596.4	574.6	532.6	519.9	450.5	30.0
HB	823.9	834.9	715.8	648.4	726.7	695.8	659.5	675.9	664.1	637.4	23.6
BL	644.0	694.2	643.3	669.6	624.3	584.3	548.7	549.6	595.9	538.0	22.5
MH	730.5	741.1	701.3	710.0	704.5	683.5	653.4	624.3	595.2	606.9	18.1
TM	774.6	705.4	799.0	791.3	771.3	714.9	766.8	677.7	595.9	617.8	22.7
CK	539.5	574.5	583.1	558.9	568.4	570.9	550.0	513.3	497.9	495.3	15.1
$\bar{x}$	724.5	746.9	721.8	713.1	705.1	676.5	652.9	626.2	592.9	578.1	23.7
±SD	108.4	99.8	100.7	100.4	78.6	82.3	79.8	85.8	73.4	83.0	4.6

Table 17.

PEAK TORQUE AND FATIGUE INDEX (LEFT LEG) DURING A 30 SECOND TEST @ 100 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-50	Fatigue Index	RPM
MS	161.1	163.8	157.1	156.5	148.6	149.8	140.3	129.0	123.2	118.6	107.3	107.0	99.6	94.5	92.0	90.8	82.5	49.6	101
AM	139.5	124.7	126.9	114.6	103.6	103.3	86.8	76.7	74.0	73.4	67.2	60.5	66.3	55.9	60.8	62.7	54.1	61.2	98
GL	145.5	148.2	137.6	130.5	130.8	131.4	119.5	121.3	110.3	107.9	96.0	96.9	98.1	87.1	83.8	83.1	80.7	45.5	99
CK	107.6	109.1	113.4	106.1	100.0	103.9	95.4	84.1	89.9	81.6	80.1	79.2	78.3	68.2	66.0	62.4	62.4	45.0	97
JG	138.2	134.5	135.4	133.3	126.2	121.7	113.1	111.9	103.6	100.6	98.1	101.2	96.3	89.3	95.1	88.3	91.7	33.6	99
HB	140.6	136.3	130.5	129.3	127.5	121.3	118.9	112.2	109.1	103.0	100.9	94.5	91.4	87.7	85.0	75.5	73.4	47.8	98
BL	147.9	155.3	144.9	138.2	136.6	125.0	127.5	116.2	109.4	103.9	99.6	94.5	85.6	97.2	83.1	89.9	86.2	44.5	99
JP	151.0	157.4	155.6	155.6	154.7	143.1	144.3	134.2	126.2	118.0	116.2	108.5	106.4	98.7	92.6	89.3	75.2	52.2	99
TM	131.7	120.4	132.4	145.2	138.5	133.6	128.1	122.9	111.0	104.2	91.7	96.0	96.0	90.2	84.4	78.6	78.6	45.9	96
TM	156.2	139.7	143.1	139.4	133.9	123.8	116.5	117.4	107.3	96.9	93.5	83.8	84.4	71.5	81.9	71.5	70.2	55.1	99
MH	117.1	114.9	109.1	106.4	102.4	99.0	93.5	87.1	84.4	79.8	81.0	72.7	73.4	65.7	57.8	55.9	55.9	52.3	97
MH	115.5	109.4	108.2	107.9	104.8	92.9	88.9	83.1	79.8	79.2	73.7	75.2	66.0	69.4	65.7	59.0	47.7	58.7	99
BQ	158.0	149.8	139.7	141.2	137.2	122.3	118.9	114.0	107.9	106.1	101.5	98.4	92.0	88.6	83.1	78.9	78.9	50.1	96
BQ	151.9	147.0	133.6	133.6	126.9	119.2	112.5	108.8	109.7	101.8	99.0	94.8	94.8	89.6	85.6	81.9	76.6	49.6	101
CH	115.8	111.3	108.8	110.0	107.9	104.2	96.6	91.4	91.4	86.5	83.1	82.5	78.9	76.4	72.4	68.2	73.4	36.6	98
CH	109.4	113.1	104.8	105.5	101.5	98.1	92.3	91.7	86.8	90.2	83.1	77.0	81.9	71.5	63.9	72.0	72.0	36.3	96
$\bar{x}$	136.7	133.4	130.1	128.3	123.8	118.3	112.1	106.4	101.5	97.0	92.0	88.9	86.8	81.3	78.3	75.5	72.5	47.8	98.3
±SD	18.2	18.9	16.9	17.7	18.0	16.7	18.1	18.0	15.2	13.8	13.0	13.5	12.0	12.9	12.0	11.5	12.0	7.7	1.6

Table 18.

PEAK TORQUE AND FATIGUE INDEX (RIGHT LEG) DURING A 30 SECOND TEST @ 100 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-50	Fatigue Index	RPM
MS	144.3	153.4	147.9	133.0	127.8	130.8	120.1	125.0	115.5	111.3	105.5	98.1	97.2	87.1	87.4	81.3	82.1	46.5	101
AM	148.6	148.6	147.0	151.9	140.6	121.3	123.8	103.6	100.3	99.3	94.8	83.4	81.6	81.0	78.6	73.4	64.2	57.7	98
GL	146.1	138.8	133.6	133.3	124.7	125.0	124.7	120.1	120.4	115.8	112.2	107.0	103.6	99.3	99.3	97.5	100.9	30.9	99
CK	124.1	121.7	123.2	115.5	113.1	111.9	105.1	100.6	107.9	104.2	92.6	92.3	89.3	82.2	74.0	70.3	73.4	40.9	97
JG	138.8	133.9	135.7	140.3	137.2	135.1	128.4	125.3	113.1	110.3	113.7	112.5	113.1	110.7	114.9	108.5	110.0	21.6	99
HB	158.6	151.6	147.9	148.2	143.7	138.8	134.2	129.3	120.7	118.9	115.2	110.3	109.7	101.5	96.3	92.9	91.7	42.2	98
BL	128.4	138.2	141.5	128.1	122.6	129.6	132.4	115.5	101.8	103.9	101.8	91.1	78.9	90.8	84.7	84.7	80.7	43.0	99
JP	142.7	158.0	155.6	159.6	158.0	151.9	147.9	148.6	143.7	126.5	127.8	121.3	128.1	113.1	109.7	103.9	109.6	31.3	99
TM	141.4	132.5	152.5	159.7	145.5	148.7	149.0	145.5	135.1	127.2	96.8	103.8	116.4	100.3	80.3	78.5	78.5	50.8	96
TM	177.0	157.7	167.8	159.9	148.9	142.4	134.5	127.2	118.0	111.3	110.3	103.0	100.3	99.3	91.7	92.0	87.1	50.8	99
MH	151.2	146.8	145.5	136.3	126.5	123.4	115.5	106.3	102.8	96.5	97.4	88.6	84.8	82.6	75.3	69.9	69.9	53.8	97
MH	143.7	136.9	132.7	124.7	116.8	116.2	112.8	103.0	96.9	95.4	86.2	88.0	73.4	75.5	74.6	70.0	56.4	60.8	99
BQ	145.5	138.2	135.4	131.7	125.3	121.3	117.4	114.9	111.3	111.3	107.9	99.3	102.4	91.7	89.6	90.8	90.8	37.6	96
BQ	143.1	150.1	141.5	138.5	131.4	127.8	127.2	122.6	118.9	119.2	111.0	107.3	106.4	99.3	95.7	97.5	89.4	40.4	101
GH	127.5	131.8	123.7	126.2	119.6	119.6	109.1	110.1	107.6	100.9	96.5	94.9	91.7	79.7	82.2	75.3	66.4	49.6	98
GH	125.0	118.9	111.3	111.0	107.0	103.9	97.2	92.0	85.6	84.4	80.4	76.7	81.6	71.5	67.6	64.2	64.2	48.6	96
$\bar{x}$	142.8	141.1	140.2	137.4	130.5	128.0	123.7	118.1	110.4	108.5	102.9	98.6	97.4	91.6	87.6	84.4	82.2	44.2	98.3
±SD	13.3	11.9	13.9	15.2	14.0	13.0	14.3	15.6	15.6	11.7	11.9	11.8	15.3	12.3	13.2	13.5	16.2	10.4	1.6

Table 19.

PEAK TORQUE AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST AT 100 RPM ($\bar{x}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-50	Fatigue Index	R.P.M.
MS	152.7	158.6	152.5	144.7	138.2	140.3	130.2	127.0	119.4	114.9	106.4	102.6	98.4	90.8	89.7	86.0	82.3	48.1	101
AM	144.0	136.6	136.9	133.3	122.1	112.3	105.3	90.2	87.1	86.4	81.0	72.0	74.0	68.5	69.7	68.0	59.1	59.0	98
GL	145.8	143.5	135.6	131.9	127.8	128.2	[illegible]	120.7	115.4	111.9	104.1	101.9	100.9	93.2	91.5	90.3	90.8	37.7	99
CK	115.8	115.4	118.3	110.8	106.5	107.9	100.3	92.3	98.9	92.9	86.4	85.7	83.8	75.2	70.0	66.3	67.9	42.6	97
JG	138.5	134.2	135.6	136.8	131.7	128.4	120.7	118.6	108.4	105.5	105.9	106.8	104.7	100.0	103.0	98.4	100.9	27.1	99
JP	146.9	157.7	155.6	157.6	156.3	147.5	146.1	141.4	135.0	122.3	122.0	114.9	117.2	105.9	101.2	96.9	92.4	41.4	99
HB	149.6	144.0	139.2	138.8	135.6	130.1	126.5	120.7	114.9	111.0	108.1	102.4	100.6	94.6	90.6	84.2	82.5	44.9	98
BL	138.2	146.7	143.2	133.1	129.6	127.3	129.9	115.8	105.6	103.9	100.7	92.8	82.2	94.0	83.9	87.3	83.4	43.2	99
TM	136.6	126.5	142.4	152.5	142.0	141.1	138.5	134.2	123.0	115.7	94.2	99.9	106.2	95.2	82.4	78.5	78.3	48.7	96
TH	166.6	148.7	155.4	149.6	141.4	133.1	125.1	122.3	112.6	104.1	101.9	93.4	92.3	85.4	86.8	81.8	78.6	52.8	99
MH	129.6	123.2	120.4	116.3	110.8	104.5	100.9	93.1	88.3	87.3	79.9	81.6	69.7	72.4	70.2	64.5	52.0	59.9	99
MH	134.1	130.9	127.3	121.4	114.5	111.2	104.5	96.7	93.6	88.1	89.2	80.7	79.1	74.1	66.5	62.9	62.7	53.2	97
GH	121.7	121.5	116.3	118.1	113.7	111.9	102.9	100.7	99.5	93.7	89.8	88.7	85.3	78.1	77.3	71.7	69.9	42.6	98
GH	117.2	116.0	108.1	108.2	104.2	101.0	94.8	91.9	86.2	87.3	81.8	76.9	81.8	71.5	65.7	68.1	67.9	42.1	96
BQ	151.8	144.0	137.6	136.5	131.3	121.8	118.1	114.5	109.6	108.7	104.7	98.9	97.2	90.2	86.4	84.8	84.6	44.3	96
BQ	147.5	148.6	137.6	136.0	129.1	123.5	119.8	115.7	114.3	110.5	105.0	101.0	100.6	94.5	90.6	89.7	83.0	44.1	101
$\bar{x}$	139.8	137.3	135.1	132.9	127.2	123.1	117.9	112.2	107.0	102.8	97.6	93.8	92.1	86.5	83.0	79.9	77.3	45.7	98.3
±SD	13.8	13.9	14.0	14.6	14.4	13.9	15.0	16.1	13.9	11.8	11.9	11.9	13.1	11.5	12.1	11.6	13.1	8.0	1.6

Table 20.

PEAK POWER AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST @ 100 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-50	Fatigue Index
HS	1614.6	1677.6	1612.9	1530.5	1461.0	1483.6	1377.0	1343.0	1262.2	1215.4	1124.9	1084.4	1040.8	960.0	948.7	909.9	870.3	48.1
AM	1478.0	1401.9	1405.1	1367.4	1253.0	1152.6	1080.5	925.2	893.7	886.0	831.1	738.6	759.0	702.5	715.1	697.8	606.4	59.0
GL	1511.3	1487.5	1405.2	1367.1	1324.4	1329.1	1265.7	1251.5	1196.0	1159.6	1078.8	1056.6	1045.5	966.3	948.9	936.2	941.0	37.7
CK	1176.5	1171.9	1201.4	1125.3	1081.9	1095.8	1018.2	937.5	1004.2	943.7	877.0	870.8	850.6	763.7	710.9	673.6	689.2	42.6
JG	1435.3	1390.9	1405.2	1417.8	1365.5	1330.7	1251.5	1229.3	1123.2	1093.1	1097.8	1107.3	1085.2	1036.0	1088.3	1020.2	1045.5	27.1
HB	1535.2	1477.2	1428.6	1423.9	1391.0	1334.5	1298.4	1238.8	1179.3	1138.5	1108.7	1050.7	1031.9	970.7	929.9	864.1	846.8	44.9
BL	1432.1	1520.8	1484.4	1379.8	1343.4	1319.6	1346.5	1200.8	1094.7	1077.2	1044.0	961.6	852.3	974.3	869.7	904.6	865.0	43.2
JP	1522.4	1634.9	1612.7	1633.3	1620.6	1528.7	1514.5	1465.4	1398.8	1267.3	1264.2	1191.3	1215.1	1097.8	1048.7	1001.2	957.6	41.4
TM	1372.7	1271.4	1431.4	1532.8	1427.2	1418.5	1392.4	1348.8	1236.5	1162.9	947.3	1003.8	1067.4	957.1	827.8	789.1	787.0	48.7
TM	1726.7	1541.4	1611.1	1550.9	1465.4	1379.8	1300.6	1267.3	1167.5	1078.8	1056.6	967.9	956.8	885.5	899.8	847.5	815.1	52.8
MH	1361.9	1328.8	1293.0	1232.5	1162.5	1129.4	1061.3	982.1	950.5	895.0	906.1	819.2	803.0	753.0	675.7	639.0	636.7	53.2
MH	1343.4	1276.8	1248.3	1205.5	1148.5	1083.6	1045.5	964.8	915.6	904.6	828.5	845.9	722.4	750.9	727.1	668.5	539.4	59.9
BQ	1525.8	1447.1	1382.5	1371.8	1319.6	1224.3	1187.5	1150.6	1101.4	1098.2	1052.3	993.9	977.0	906.3	867.9	852.6	850.3	44.3
BQ	1559.8	1570.9	1454.6	1438.4	1365.7	1305.9	1267.1	1223.4	1208.9	1168.5	1110.3	1068.3	1063.4	998.8	958.4	948.7	877.7	44.1
GH	1248.4	1246.7	1192.8	1212.1	1167.0	1148.2	1055.4	1033.6	1020.7	961.5	921.5	910.3	875.2	801.0	793.6	735.9	717.2	42.6
GH	1178.2	1165.9	1086.1	1087.6	1047.7	1015.4	952.4	923.2	866.4	877.1	821.8	772.7	821.8	718.9	660.5	684.4	682.4	42.1
$\bar{x}$	1438.9	1413.2	1391.0	1367.3	1309.0	1267.5	1213.4	1155.3	1101.2	1057.6	1004.4	965.2	948.0	890.2	854.4	823.3	795.6	45.7
±SD	153.1	158.4	155.2	158.1	155.7	151.0	161.2	172.3	149.6	128.2	130.5	129.1	139.4	124.3	131.5	126.6	139.1	8.0

Table 21.

AVERAGE POWER AND FATIGUE INDEX (SUM OF BOTH LEGS) DURING A 30 SECOND TEST @ 100 RPM

NAME	1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-50	Fatigue Index
	Pedal Cycle Number																	
MS	993.5	1012.3	960.3	923.6	859.6	863.4	820.7	761.1	740.4	723.6	722.2	688.7	633.2	618.5	603.0	548.6	541.2	46.5
AM	958.7	898.2	874.9	860.0	812.9	756.3	673.3	574.4	589.2	561.1	545.7	493.7	512.4	487.3	502.9	559.0	524.2	45.3
GL	1038.5	1106.7	1045.3	1038.7	950.6	933.9	929.5	895.7	831.1	785.1	770.5	765.8	713.2	678.5	682.1	651.5	564.7	49.0
CK	800.9	791.1	802.7	757.2	758.0	724.4	693.0	655.8	709.3	659.9	606.4	586.8	585.1	556.5	504.2	463.1	460.1	42.7
JG	877.9	865.9	861.2	836.9	806.1	759.5	700.2	668.0	605.5	587.7	596.4	592.2	582.2	542.0	590.1	562.9	548.3	37.5
HB	945.1	1008.6	973.3	973.3	951.5	895.4	851.1	797.5	768.1	727.3	689.4	692.5	674.6	628.4	609.2	560.3	545.7	45.9
BL	1008.4	1031.4	1024.4	955.6	913.5	893.4	931.0	789.6	739.4	719.5	668.3	664.3	635.1	690.0	581.7	585.0	578.1	43.9
JP	878.7	948.0	888.1	891.0	880.8	810.5	820.4	795.6	765.3	671.1	691.3	665.7	664.3	612.1	588.5	582.8	549.4	42.0
TH	849.0	802.8	874.3	930.7	863.9	865.4	840.4	804.7	780.0	742.8	601.6	671.1	656.9	569.9	509.0	448.3	448.3	51.8
TM	1064.6	996.6	1026.2	1030.6	968.1	891.8	843.4	810.0	790.6	756.9	726.8	630.4	642.1	554.0	585.4	560.8	507.5	52.3
MH	1030.0	1022.5	1011.0	978.2	943.3	879.7	855.9	791.5	812.5	787.1	755.3	684.1	646.6	589.0	569.4	580.6	580.6	43.6
MH	1039.8	971.5	918.7	810.0	795.9	797.9	753.5	661.2	645.0	660.2	571.8	627.2	534.1	503.8	552.7	479.2	399.6	61.6
BQ	1004.0	965.7	972.3	945.5	864.9	812.8	791.4	721.6	714.4	700.7	669.2	609.0	585.4	569.9	558.8	511.5	511.5	49.1
BQ	1128.8	1138.8	991.6	968.2	938.8	899.9	846.6	822.3	772.0	721.4	651.7	619.3	622.3	592.1	558.1	547.5	519.6	54.4
GH	734.4	674.0	661.4	714.4	651.5	631.9	574.5	590.4	561.0	495.8	481.1	464.0	433.4	432.4	425.7	359.7	380.9	48.1
GH	737.8	735.6	679.3	664.3	623.5	599.4	578.7	542.8	509.6	499.6	483.8	405.2	447.9	383.5	344.9	372.8	372.8	49.5
$\bar{x}$	943.1	935.6	910.3	892.4	848.9	813.5	781.5	730.1	708.3	675.0	639.5	616.3	598.1	563.0	547.9	523.5	502.0	47.7
±SD	118.1	131.1	116.7	110.2	103.9	98.0	109.6	102.6	96.9	93.0	89.1	93.2	80.1	81.6	78.8	79.5	68.9	5.7

Table 22.

PEAK TORQUE AND FATIGUE INDEX (LEFT LEG) DURING A 30 SECOND TEST AT 140 RPM ($\bar{X}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-51	52-54	55-57	58-60	61-63	64-66	67-70	Fatigue Index	RPM
CK	89.6	84.7	86.8	83.8	80.4	76.7	72.7	64.5	52.6	47.1	53.5	55.3	44.6	38.8	37.3	36.4	34.5	30.0	27.5	27.8	25.1	26.6	26.6	70.2	130
CK	87.7	91.1	85.6	83.1	81.3	74.3	73.7	73.4	70.3	64.8	65.1	60.8	57.2	55.3	55.0	52.9	43.1	40.0	37.9	36.4	35.8	34.8	35.8	60.7	135
JG	80.1	83.4	79.2	75.2	66.0	63.3	55.0	54.4	53.2	55.0	54.1	52.3	57.2	56.9	59.0	61.7	56.2	58.7	58.1	54.4	56.9	54.4	53.2	36.2	133
HS	104.5	105.5	96.9	84.1	82.8	87.4	80.1	83.8	71.2	65.7	69.7	65.1	64.2	59.0	62.4	58.7	61.4	57.2	56.5	60.8	56.9	56.9	56.9	46.1	135
SH	106.7	108.2	98.7	91.7	86.8	82.5	77.0	74.0	71.8	70.0	62.7	59.9	57.8	52.9	52.0	51.7	51.7	48.9	45.9	45.2	41.6	38.2	41.3	61.8	134
BQ	121.7	116.5	114.9	111.0	100.0	88.9	88.6	84.4	75.8	77.0	70.9	67.6	68.2	64.5	64.2	62.1	58.4	59.3	55.3	57.8	55.0	49.2	55.9	54.1	135
GL	128.7	144.3	132.0	116.8	105.1	98.1	92.0	[illegible]	84.7	84.4	86.2	80.7	81.3	78.9	74.3	74.3	71.8	68.5	64.8	63.3	61.7	58.1	57.2	60.4	137
MH	86.2	75.8	75.2	72.1	66.0	65.1	62.4	62.4	60.8	59.3	55.9	56.9	55.9	49.8	48.3	46.5	44.9	42.5	39.7	35.2	33.9	33.0	29.3	66.0	135
TH	110.0	107.6	106.1	100.0	93.5	95.7	88.3	82.5	79.2	74.3	69.4	65.7	63.0	58.1	55.6	46.5	49.8	46.2	50.7	39.1	39.4	36.7	29.3	73.4	134
GH	84.7	78.6	69.1	64.5	60.8	64.4	61.1	54.7	59.9	55.0	52.9	58.1	51.7	50.7	51.7	43.4	47.7	52.6	43.7	47.7	50.7	46.5	39.0	54.0	135
HH	111.0	115.2	108.2	104.5	92.9	88.6	84.1	74.9	73.4	69.7	67.2	61.1	56.5	62.4	66.6	55.3	52.0	50.4	51.0	45.9	41.0	41.3	36.7	68.1	134
HB	102.4	100.9	96.3	92.3	82.5	79.8	77.9	74.6	65.7	63.3	61.7	57.8	58.1	54.4	60.2	52.6	55.0	47.7	49.5	48.0	50.7	37.9	40.3	60.6	135
BL	144.3	139.7	137.9	123.8	119.5	103.6	100.3	90.8	98.7	95.7	82.5	85.3	83.4	73.1	72.7	64.2	68.5	70.3	58.7	61.4	70.9	54.1	53.2	63.1	138
BL	143.1	140.0	132.4	131.1	118.9	108.2	92.9	90.2	94.1	85.6	74.0	73.7	70.3	65.7	62.7	61.1	60.2	60.5	55.0	53.5	58.1	52.9	55.0	61.6	134
JP	98.1	111.9	102.4	100.9	90.8	90.5	89.3	80.7	81.0	68.2	61.4	73.1	64.5	62.7	48.3	53.8	60.5	51.4	57.5	55.3	50.7	47.4	51.4	54.1	134
JP	98.7	98.7	97.2	85.3	86.8	82.5	76.4	72.7	71.2	62.7	55.9	62.1	58.4	58.4	61.4	49.2	44.3	47.4	52.6	54.1	46.8	44.0	38.2	61.3	137
AM	82.5	88.6	78.9	78.6	73.1	74.0	67.2	64.2	60.5	56.2	56.2	54.7	51.0	49.2	51.7	45.2	45.5	42.2	44.0	40.3	34.8	34.8	32.6	63.2	135
AM	78.3	74.9	77.0	71.8	66.9	63.9	56.7	55.9	55.9	54.4	49.5	47.4	48.3	48.0	44.9	41.9	41.0	44.9	37.9	39.4	33.0	32.1	26.1	66.7	135
$\bar{X}$	103.2	103.6	98.6	92.8	86.3	82.5	77.6	73.4	71.1	67.1	63.8	63.2	60.6	57.7	57.1	53.2	52.6	51.0	49.2	48.1	46.8	43.3	42.1	60.1	134.7
±SD	20.4	21.8	20.6	18.9	17.0	14.0	13.2	11.8	13.1	12.6	10.3	9.9	10.3	9.5	9.6	9.4	9.8	10.1	9.4	10.2	12.0	9.6	11.2	8.8	1.7

Table 23.

PEAK TORQUE AND FATIGUE INDEX (RIGHT LEG) DURING A 30 SECOND TEST AT 140 RPM ($\bar{x}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-51	52-54	55-57	58-60	61-63	64-66	67-70	Fatigue Index
CK	101.8	98.4	100.3	93.3	98.4	92.6	86.5	66.6	65.1	52.3	67.2	53.5	60.8	52.3	53.2	55.0	53.5	48.9	46.5	50.1	46.5	45.4	45.4	55.4
CK	80.7	89.6	90.8	90.5	85.6	83.1	77.3	77.6	75.8	71.5	64.8	63.9	57.5	54.4	55.0	52.3	42.5	37.6	38.5	36.7	36.7	35.2	31.6	65.2
JG	116.2	120.4	117.1	111.0	107.0	106.7	94.5	88.3	91.7	77.0	73.4	76.1	71.8	67.2	70.0	70.3	61.7	71.5	60.2	54.4	61.1	60.5	70.6	41.4
HS	114.9	107.9	104.8	103.9	93.5	95.4	88.6	89.9	87.4	68.5	68.8	69.1	63.6	63.9	58.1	64.2	64.2	57.2	60.2	55.9	51.0	48.6	41.3	64.1
SM	106.7	104.5	102.1	96.6	94.8	91.7	87.1	81.9	82.5	82.2	77.3	73.4	73.4	71.5	65.7	65.7	63.6	63.6	59.9	55.0	56.2	54.1	48.6	54.5
BQ	126.2	123.5	122.6	115.2	111.3	106.7	100.3	98.4	90.5	88.9	85.3	80.1	74.3	75.8	74.3	67.9	64.5	63.9	62.7	56.2	57.5	52.3	45.9	63.6
GL	126.9	124.4	116.8	111.9	106.4	99.0	93.2	87.1	83.4	86.2	81.0	82.8	77.3	79.5	81.6	73.4	73.4	73.4	70.3	67.2	67.6	61.7	60.2	52.6
MH	97.8	85.3	89.3	82.2	81.3	79.2	74.0	73.1	73.1	71.8	69.7	69.4	66.3	63.6	61.7	61.7	59.0	55.0	54.7	52.0	54.7	52.0	49.5	49.4
TM	111.9	104.5	97.2	90.8	78.6	80.7	75.2	67.2	61.1	57.8	55.0	48.6	52.3	48.0	43.7	42.5	38.5	45.5	44.3	36.7	36.7	36.7	44.0	60.7
GB	79.5	75.2	67.9	57.8	52.3	54.7	53.2	49.2	51.0	46.8	41.3	48.0	39.4	37.6	44.6	29.3	38.8	42.8	34.5	41.6	37.0	31.2	24.3	69.4
HB	131.2	133.7	131.2	126.9	112.0	102.6	99.2	94.5	90.5	76.2	81.2	77.8	71.5	71.5	83.7	69.0	65.3	65.9	67.2	59.1	44.2	49.8	46.7	65.1
HB	118.6	108.2	102.7	101.8	91.4	86.2	80.7	76.7	70.9	69.7	67.9	64.2	64.2	64.2	69.1	62.1	63.9	55.0	52.9	59.3	53.2	45.9	45.9	61.3
BL	145.5	134.5	132.0	120.1	114.6	100.0	96.9	92.6	96.9	78.3	75.8	80.7	71.5	74.6	75.2	62.4	67.9	65.4	60.5	66.0	64.2	53.5	49.5	66.0
BL	148.7	153.6	146.2	132.2	119.4	113.5	105.7	102.6	92.7	90.5	85.2	78.7	78.7	71.5	76.5	74.3	65.3	66.6	68.4	59.1	59.1	56.0	54.1	63.6
JP	101.9	115.1	104.4	104.4	98.1	99.3	94.0	85.4	84.8	74.0	73.7	83.2	72.8	72.8	66.4	66.4	69.3	60.1	66.4	66.4	63.9	57.9	50.3	56.3
JP	111.9	111.3	107.0	99.3	100.6	93.5	90.5	88.6	84.4	79.5	74.9	79.2	76.4	77.9	68.5	74.3	66.6	57.8	63.3	62.4	54.1	55.3	54.4	51.4
AM	100.9	103.6	97.5	91.7	85.0	81.6	70.9	65.4	62.7	58.1	57.8	55.0	55.9	57.8	55.3	55.3	48.0	46.5	44.9	49.5	48.6	37.9	40.8	60.6
AM	91.7	88.3	86.5	85.6	79.2	71.2	67.6	62.4	62.4	56.5	56.9	54.7	60.8	54.7	56.2	54.1	48.0	47.7	43.1	49.5	49.8	48.0	39.0	57.5
$\bar{x}$	111.8	110.1	106.5	101.2	95.0	91.0	85.3	80.4	78.2	71.4	69.8	68.8	66.0	64.4	64.4	61.1	58.6	56.9	55.5	54.3	52.3	49.0	46.8	58.8
±SD	19.3	19.6	18.8	17.5	16.4	14.4	13.5	14.2	13.4	12.7	11.5	12.2	10.3	11.5	11.7	11.7	10.9	10.3	11.0	9.2	9.5	8.9	10.2	7.1

Table 24.

PEAK TORQUE AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST AT 140 RPM ($\bar{x}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-51	52-54	55-57	58-60	61-63	64-66	67-70	Fatigue Index
CK	96.4	91.5	93.5	91.5	89.4	84.7	79.6	65.6	58.8	49.7	60.4	54.5	52.7	45.5	45.2	45.[illegible]	44.0	39.4	37.0	39.0	35.8	36.0	36.0	62.7
CK	84.2	90.3	88.2	86.8	83.4	78.7	75.5	75.7	73.1	68.2	65.0	62.4	57.3	54.9	55.0	52.6	42.8	38.8	38.2	36.5	36.2	35.0	33.7	62.7
JG	98.1	101.9	98.1	93.1	86.5	85.0	74.7	71.4	72.4	66.0	63.7	64.2	64.5	62.1	64.5	66.0	59.0	65.1	59.1	54.4	59.0	57.5	61.9	39.3
HS	109.7	106.7	100.9	94.0	88.2	91.4	84.4	86.8	79.3	67.1	69.2	67.1	63.9	61.4	60.2	61.4	62.8	57.2	58.4	58.4	54.0	52.7	49.1	55.2
SH	106.7	106.4	100.4	94.1	90.8	87.1	82.1	77.9	77.2	76.1	70.0	66.6	65.6	62.2	58.8	58.7	57.6	56.2	52.9	50.1	48.9	46.2	44.9	57.9
BQ	123.9	120.0	118.8	113.1	105.6	97.8	94.5	91.4	83.1	83.0	78.1	73.8	71.2	70.2	69.2	65.0	61.4	61.6	59.0	57.0	56.2	50.7	50.9	58.9
GL	127.8	134.3	124.4	114.3	105.8	98.6	92.6	85.4	84.1	85.3	83.6	81.8	79.3	79.2	77.9	73.8	72.6	70.9	67.6	65.3	64.6	59.9	58.7	56.3
HH	92.0	80.5	82.2	77.2	73.7	72.1	68.2	67.7	66.9	65.6	62.8	63.1	61.1	56.7	55.0	54.1	52.0	48.8	47.2	43.6	44.3	42.5	39.4	57.2
TM	111.0	106.1	101.6	95.4	86.0	88.2	81.8	74.9	70.2	66.0	62.2	57.2	57.6	53.0	49.7	44.5	44.2	45.9	47.5	37.9	38.1	36.7	36.7	66.9
GH	82.1	76.9	68.5	61.1	56.5	58.1	57.2	52.0	55.5	50.9	47.1	53.0	45.5	44.2	48.1	36.4	43.3	47.7	39.1	44.6	43.9	38.8	31.6	61.5
HB	121.1	124.5	119.7	115.7	102.4	95.6	91.6	84.7	81.9	72.9	74.2	69.4	64.0	66.9	75.1	62.2	58.6	58.2	59.1	52.5	42.6	45.5	41.7	66.5
HB	110.5	104.5	99.5	97.0	87.0	83.0	79.3	75.7	68.3	66.5	64.8	61.0	61.1	59.3	64.6	57.3	59.5	51.4	51.2	53.6	52.0	41.9	43.1	61.0
BL	144.9	137.1	135.0	122.0	117.1	101.8	98.6	91.7	97.8	87.0	79.2	83.0	77.5	73.8	74.0	63.3	68.2	67.9	59.6	63.7	67.6	53.8	51.5	64.5
BL	145.9	146.8	139.3	131.7	119.2	110.9	99.3	96.4	93.4	88.0	79.6	76.2	74.5	68.6	69.6	67.7	62.8	63.5	61.7	56.3	58.6	54.4	54.6	62.8
JP	100.0	113.5	103.4	102.6	94.4	94.9	91.6	83.1	82.9	71.1	67.6	78.1	68.6	67.7	57.4	60.1	64.9	55.7	61.9	60.9	57.3	52.6	50.8	55.2
JP	105.3	105.0	102.1	92.3	93.7	88.0	83.4	80.7	77.8	71.1	65.4	70.6	67.4	68.2	65.0	61.7	55.5	52.6	57.9	58.2	50.4	49.7	46.3	56.0
AH	91.7	96.1	88.2	85.1	79.0	77.8	69.1	64.8	61.6	57.2	57.0	54.9	53.5	53.5	53.5	50.3	46.8	44.3	44.5	44.9	41.7	36.4	36.7	61.8
AH	85.0	81.6	81.8	78.7	73.1	67.6	62.2	59.1	59.1	55.5	53.2	51.0	54.6	51.4	50.6	48.0	44.5	46.3	40.5	44.5	41.4	40.0	32.6	61.6
$\bar{x}$	107.6	106.9	102.5	97.0	90.7	86.7	81.4	74.6	74.6	69.3	66.8	66.0	63.3	61.0	60.7	57.2	55.6	54.0	52.4	51.2	49.6	46.1	44.5	59.3
±SD	19.1	19.8	18.7	17.4	15.6	12.9	12.1	12.0	11.8	11.6	9.6	9.9	9.0	9.6	9.8	9.5	9.4	9.5	9.5	8.9	9.7	8.0	9.1	6.2

Table 25.

PEAK POWER AND FATIGUE INDEX ($\bar{x}$ OF BOTH LEGS) DURING A 30 SECOND TEST @ 140 RPM ($\bar{x}$ OF 3 PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	16 - 18	19 - 21	22 - 24	25 - 27	28 - 30	31 - 33	34 - 36	37 - 39	40 - 42	43 - 45	46 - 48	49 - 51	52 - 54	55 - 57	58 - 60	61 - 63	64 - 66	67 - 70	Fatigue Index
JC	1366.3	1419.5	1366.3	1296.1	1204.6	1183.3	1040.7	993.9	1008.8	919.4	887.5	893.9	898.1	864.1	898.1	919.4	821.5	906.6	823.6	757.6	821.5	800.2	861.9	39.3
HS	1551.0	1507.8	1425.7	1328.5	1246.4	1291.8	1192.4	1227.0	1121.2	948.3	978.6	948.3	903.0	868.4	851.1	868.4	887.9	807.9	825.2	825.2	762.6	745.3	693.4	55.2
SM	1496.7	1492.4	1408.8	1320.8	1273.7	1222.2	1151.4	1093.6	1082.8	1067.8	982.1	934.9	919.9	872.7	825.5	823.4	808.4	789.1	741.9	703.3	686.2	647.6	630.4	57.9
BQ	1751.9	1695.8	1678.5	1598.6	1492.7	1382.5	1335.0	1291.8	1175.2	1173.0	1103.9	1043.4	1006.7	991.5	978.6	918.1	868.4	870.6	833.8	805.8	795.0	717.2	719.4	58.9
CL	1812.7	1927.0	1784.5	1639.8	1517.0	1414.0	1328.5	1225.5	1205.7	1223.3	1199.1	1172.8	1137.8	1135.6	1118.0	1058.8	1041.3	1017.2	969.0	936.1	927.3	859.4	841.8	56.3
HH	1300.4	1138.4	1162.2	1090.9	1041.2	1019.6	963.5	957.0	946.2	926.7	887.9	892.2	864.1	801.4	777.7	764.7	734.5	689.1	667.5	615.7	626.5	600.5	556.9	57.2
TH	1556.7	1488.1	1425.9	1338.0	1207.2	1237.2	1147.2	1050.7	984.2	926.3	872.7	801.9	808.4	744.0	696.9	624.0	619.7	643.3	666.9	531.8	533.9	514.1	514.6	66.9
CH	1160.4	1086.6	967.8	864.1	799.3	820.9	807.9	734.5	784.2	719.4	665.3	749.6	643.7	624.3	680.5	514.1	611.3	674.0	553.0	630.8	620.0	548.7	447.2	61.5
AH	1296.3	1358.8	1246.4	1203.2	1116.8	1099.6	976.4	915.9	870.6	807.9	805.8	775.5	756.1	756.1	756.1	710.7	661.3	626.5	628.6	635.1	589.7	514.1	518.5	61.8
AH	1201.4	1151.6	1155.7	1112.5	1032.6	954.8	879.2	836.0	836.0	784.2	751.8	721.5	771.2	725.8	715.0	678.3	628.6	654.5	572.5	628.6	585.4	566.0	460.8	61.6
JP	1402.8	1592.5	1450.6	1439.9	1324.7	1331.5	1285.2	~~1165.2~~	1162.9	997.4	948.0	1096.1	962.8	949.9	804.8	843.4	910.5	781.8	869.1	854.1	804.2	738.4	713.1	55.2
JP	1510.4	1506.1	1464.4	1324.1	1343.8	1262.7	1197.0	1157.5	1115.8	1019.4	938.3	1012.8	966.8	977.7	931.7	885.7	795.8	754.1	830.9	835.2	723.4	712.5	664.2	56.0
BL	2046.3	2059.8	1953.8	1847.1	1671.8	1555.5	1393.6	1352.5	1310.5	1235.2	1116.7	1068.7	1045.1	962.8	976.2	950.3	880.6	891.4	865.9	789.7	821.9	763.6	765.6	62.8
BL	2093.6	1980.8	1949.9	1762.2	1691.5	1470.7	1424.3	1324.9	1413.3	1256.5	1143.9	1199.1	1119.6	1066.6	1068.8	914.2	984.9	980.5	861.2	920.8	976.0	777.3	742.7	64.5
HB	1699.0	1746.5	1679.7	1623.4	1437.2	1341.8	1285.6	1188.6	1149.5	1023.4	1041.1	974.3	898.5	939.2	1054.3	872.4	822.7	816.3	829.3	736.1	597.1	638.5	584.6	66.5
HB	1561.8	1477.6	1406.3	1371.7	1229.2	1173.0	1121.2	1069.3	965.6	939.7	915.9	861.9	864.1	838.2	913.8	810.1	840.3	725.8	723.7	758.2	734.5	591.9	609.2	61.0
CK	1190.3	1276.7	1246.4	1227.0	1179.5	1112.5	1067.2	1067.2	1032.6	963.5	918.1	881.4	810.1	775.5	777.7	743.1	604.9	548.7	540.1	516.3	512.0	494.7	476.3	62.7
CK	1312.1	1246.0	1273.1	1246.0	1216.9	1152.4	1038.8	892.4	800.9	676.1	821.7	740.6	717.7	619.9	615.7	622.0	599.1	536.7	503.4	530.5	486.8	489.9	489.9	62.7
$\bar{x}$	1518.3	1508.6	1447.0	1368.6	1279.2	1223.7	1148.9	1085.8	1053.7	978.2	948.8	931.6	894.1	861.9	857.8	806.7	784.5	761.9	739.2	722.8	700.2	651.1	627.2	59.3
1SD	277.9	286.6	271.0	248.8	224.9	184.3	175.0	173.4	172.8	169.8	139.2	145.9	133.0	141.7	144.1	137.5	137.5	137.9	137.4	131.1	141.3	116.5	130.3	6.2

Table 26.

AVERAGE POWER AND FATIGUE INDEX (SUM OF BOTH LEGS) DURING A 30 SECOND TEST AT 140 RPM ($\bar{x}$ OF THREE PEDAL CYCLES)

NAME	Pedal Cycle Number 1 - 3	4 - 6	7 - 9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-51	52-54	55-57	58-60	61-63	64-66	67-70	Fatigue Index
CK	815.5	820.9	866.5	886.8	876.4	799.8	724.5	586.1	548.7	522.5	614.0	514.8	574.3	496.4	459.4	497.7	477.4	432.8	408.9	440.0	426.9	403.7	403.7	54.5
CK	839.6	917.9	880.9	861.5	816.3	779.8	757.0	758.4	769.1	729.7	706.4	707.9	665.1	656.8	630.6	622.3	488.1	430.7	432.2	407.4	380.2	379.2	336.9	63.3
JG	970.2	957.9	952.2	870.6	793.2	769.5	741.3	733.8	677.6	663.4	578.0	619.1	608.7	550.7	591.3	603.5	513.4	542.6	499.7	469.0	488.4	492.2	511.0	47.3
HS	1054.0	1049.1	990.3	918.4	890.2	884.3	852.3	820.7	781.8	704.9	739.0	707.4	686.5	619.9	664.6	627.6	605.3	556.7	585.8	566.4	519.2	503.2	494.4	53.1
SH	1113.7	1096.9	1081.6	994.4	924.5	908.2	878.0	848.3	818.6	791.3	771.7	700.8	641.4	675.4	639.9	634.7	598.7	574.3	564.7	528.3	507.7	479.0	454.1	59.2
BQ	1110.9	1079.3	1089.0	1028.7	943.2	858.6	883.9	848.4	786.6	770.1	743.8	728.8	675.8	689.9	703.0	674.8	629.1	601.4	649.5	584.4	545.5	481.3	498.8	55.1
GL	1199.6	1227.2	1137.0	1135.0	1081.0	1035.9	986.8	923.3	882.7	847.1	858.7	842.1	835.1	792.1	796.6	776.6	739.5	788.6	703.0	693.9	631.4	619.3	581.3	52.6
MH	1049.1	1031.6	1038.0	964.1	915.0	856.1	816.3	803.1	803.1	770.1	771.5	757.0	752.1	736.1	703.0	695.7	672.4	648.5	630.1	559.1	525.5	517.3	459.4	56.2
TM	1133.8	1054.3	1010.2	976.7	927.8	851.2	816.2	748.2	655.7	616.9	560.4	548.9	540.8	501.0	493.4	445.5	372.2	418.2	388.9	328.6	343.0	325.7	304.6	73.1
GH	676.7	599.4	532.4	433.7	413.7	444.8	301.9	383.6	405.5	324.8	323.8	359.8	319.4	299.5	310.2	243.6	260.6	300.0	271.8	279.1	276.6	249.4	214.4	68.1
HB	1195.6	1197.3	1238.9	1133.4	1008.9	1006.1	950.9	895.8	857.2	754.0	810.0	772.0	690.0	794.9	838.6	668.4	581.6	667.2	668.6	602.9	439.3	437.5	438.1	64.6
HB	973.8	957.7	896.5	830.9	761.3	761.3	756.0	718.1	645.1	619.9	682.1	564.9	591.7	558.6	582.9	501.7	533.3	425.4	453.1	459.9	440.5	353.9	373.4	61.7
BL	1299.5	1255.8	1258.9	1139.0	1079.0	953.0	943.9	918.5	936.3	848.9	803.7	883.4	755.9	716.8	676.2	567.5	613.7	591.3	546.6	609.1	636.0	522.7	522.7	59.8
BL	1295.6	1370.1	1242.1	1152.5	1137.2	1066.6	932.3	949.4	867.3	891.2	850.4	806.0	808.5	651.3	644.3	642.5	588.5	624.4	598.0	530.2	521.5	483.1	480.0	65.0
JP	1001.1	1098.9	1036.8	1037.8	942.9	975.2	919.8	871.6	881.5	724.6	656.6	805.8	704.3	690.2	570.9	620.5	673.9	574.3	616.7	608.5	584.8	523.5	475.4	56.7
JP	999.4	985.8	1023.9	941.3	971.3	955.8	907.7	889.7	882.7	660.9	712.0	752.5	693.9	688.4	660.4	628.9	605.8	568.8	594.8	567.8	515.7	519.2	487.2	52.4
AM	873.6	782.7	772.0	747.7	717.6	669.0	581.9	568.8	556.7	542.1	528.9	519.7	530.9	537.7	528.0	481.8	465.3	463.3	496.6	495.4	466.7	416.2	407.7	53.3
AM	878.5	840.6	783.7	756.0	676.7	603.3	550.3	562.0	553.7	508.5	508.0	503.7	508.0	489.6	484.2	501.2	403.5	415.2	408.4	423.9	393.3	416.6	355.1	59.6
$\bar{x}$	1026.6	1018.0	990.6	933.8	882.0	844.8	794.5	768.2	739.4	682.8	678.8	671.9	643.5	619.2	609.9	579.7	545.7	534.7	527.2	508.6	480.1	451.8	433.2	58.7
±SD	169.3	187.0	184.8	177.4	170.7	157.8	173.0	154.5	149.7	143.0	138.9	142.0	122.6	125.4	125.6	119.9	119.3	118.0	116.4	105.9	95.1	88.1	89.8	6.5

Table 27.

TOTAL WORK (kJ) GENERATED BY 13 SUBJECTS DURING 30 SECS OF MAXIMAL CYCLING AT 60, 100 AND 140 RPM

NAME	60 RPM			100 RPM			140 RPM		
	RIGHT LEG	LEFT LEG	BOTH LEGS	RIGHT LEG	LEFT LEG	BOTH LEGS	RIGHT LEG	LEFT LEG	BOTH LEGS
BQ	10.95	10.72	21.67	11.52 12.12	10.65 11.34	22.17 23.46	13.30	9.95	23.25
HS	9.14 10.31	8.84 9.24	17.98 19.55	10.69	12.18	22.87	11.13	11.08	22.21
JG	11.12 9.84	9.14 8.41	20.26 18.25	11.04	9.69	20.73	12.93	7.21	20.14
SM	10.53 10.83	11.83 10.50	22.36 21.33	-	-	-	13.35	9.38	22.73
GL	14.55	12.74	27.29	14.37	11.43	25.80	13.86	12.57	26.43
AH	9.91	9.79	19.70	12.56	7.34	19.90	9.95 10.26	7.36 6.29	17.31 16.55
JP	9.46	8.42	17.88	11.66	11.11	22.77	13.08 13.62	10.14 8.99	23.22 22.61
HB	12.16	9.16	21.32	13.44	10.31	23.75	14.93 10.62	9.73 8.47	24.66 19.09
BL	9.21	9.14	18.35	11.83	12.20	24.03	13.18 13.93	11.71 11.35	24.89 25.28
MH	10.37	10.40	20.77	11.94 14.58	9.13 9.42	21.07 24.00	14.03	9.07	23.10
TM	11.83	9.93	21.76	12.14 13.70	10.00 10.33	22.14 24.03	8.52	10.50	19.02
CK	9.12	7.88	17.00	11.08	8.98	20.06	11.69 11.04	6.40 8.75	18.09 19.79
GH	-	-	-	8.75 8.42	7.80 7.48	16.55 15.90	4.30	6.57	10.87
$\bar{x}$	10.62	9.74	20.36	11.87	9.96	21.83	11.87	9.20	21.07
±SD	1.43	1.32	2.54	1.72	1.54	2.71	2.56	1.89	3.85

Table 28.

VALUES OF PLASMA LACTATE CONCENTRATION (m mol/litre) MEASURED IN 13 SUBJECTS 3 MINUTES AFTER COMPLETING 30 SECS OF MAXIMAL CYCLING AT 60, 100, AND 140 RPM

NAME	LACTATE 60 RPM	CONCENTRATION 100 RPM	140 RPM
MS	9.0	12.8	13.8
JG	5.6	10.0	-
HB	9.2	10.5	6.3
JP	6.8	12.6	9.2
SM	8.0	10.6	10.8
MH	10.8	11.0	6.2
AM	13.4	14.6	10.2
BQ	12.4	12.6	9.8
BL	5.0	7.6	6.3
TM	11.8	6.5	10.0
CK	11.4	13.0	9.0
GH	8.8	7.0	5.4
GL	13.6	8.6	12.8
$\bar{x}$	9.68	10.57	9.15
±SD	2.83	2.55	2.68

BIBLIOGRAPHY

Asmussen, E., and O. Boje (1945). Body temperature and capacity for work. Acta. Physiol. Scand. 10:1-22.

Asmussen, E., F. Bonde-Peterson and K. Jorgensen (1976). Mechano-elastic properties of human muscles at different temperatures. Acta. Physiol. Scand. 96:83-93.

Atkins, A. R., and J. D. Nicholson (1963). An accurate constant-work-rate ergometer. J. Appl. Physiol. 18:205-208.

Barany, M. (1967). ATPase activity of myosin correlated with speed of muscle shortening. J. Gen. Physiol. 50:197-218.

Barnes, W. S. (1981). Isokinetic fatigue curves at different contractile velocities. Arch. Phys. Med. Rehabil. 62:66-69.

Bar-Or, O. (1978). A new anaerobic capacity test - characteristics and applications. Proc. 21st World Cong. Sports Med. Brasilia.

Bergh, U., and B. Ekblom (1979). Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. Acta. Physiol. Scand. 107:33-37.

Bergstom, J. (1962). Muscle electrolytes in man. Scand. J. Clin. Lab. Invest. Suppl. 68.

Best, C. H., and R. C. Partridge (1928). The equation of motion of a runner, exerting a maximal effort. Proc. Roy. Soc. B. 103:218-225.

Bigland-Ritchie, B., D. A. Jones and J. J. Woods (1979). Excitation frequency and muscle fatigue: electrical responses during human voluntary and stimulated contractions. Exp. Neurol. 64:414-427.

Bigland-Ritchie, B., Y. Goto, R. Johansson and J. J. Woods (1982). Contractile speed and e.m.g. changes in fatigue of human voluntary contractions. J. Physiol. 322:45-46P.

Bigland-Ritchie, B., R. Johansson, O. C. J. Lippold and J. J. Woods (1982a). Changes of single motor unit firing rates during sustained maximal voluntary contractions. J. Physiol. 328:27-28P.

Binkhorst, R. A., L. Hoofd and A. C. A. Vissers (1977). Temperature and force-velocity relationship of human muscles. J. Appl. Physiol. 42:471-475.

Brenton, D. P., R. H. T. Edwards, S. R. Grindrod and P. S. Tofts (1981). Computerized X-ray tomography to determine human skeletal muscle size and composition in health and disease. J. Physiol. 317:3P.

Budingen, H. J., and H. J. Freund (1976). The relationship between the rate of rise of isometric tension and motor unit recruitment in human forearm muscle. Pflugers. Arch. 362:61-67.

Bulcke, J. A., J. L. Termote, Y. Palmers and D. Crolla (1979). Computed tomography of the human skeletal muscular system. Neuroradiology. 17:127-136.

Buller, A. J., and W. F. H. M. Mommaerts (1968). Myofibrillar ATPase as a determining factor for contraction velocity, and its changes upon experimental cross-innervation. J. Physiol. 46-47P.

Burke, R. E., D. N. Levine, T. Tsairis and F. E. Zajac, III (1973). Physiological types and histochemical profiles in motor units of the cat gastrocnemius. J. Physiol. 234:723-748.

Burke, R. E. Motor units: anatomy, physiology, and functional organization. IN: <u>Handbook of Physiology</u>., <u>The Nervous System</u>, Bethesda, MD: Am. Physiol. Soc. 1981. Sect. 1, vol. 11, ch. 10, p. 345-422.

Carlson, F. D., and D. R. Wilkie. <u>Muscle Physiology</u>. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974, p. 43.

Cathcart, E. P., D. T. Richardson and W. Campbell (1923). Studies in muscle activity. 11. The influence of speed on the mechanical efficiency. J. Physiol. 58:355-361.

Close, R. (1964). Dynamic properties of fast and slow skeletal muscles of the rat during development. J. Physiol. 173:74-95.

Close, R. (1965). Force:velocity properties of mouse muscles. Nature. 206:718-719.

Close, R., and J. F. Y. Hoh (1967). Force:velocity properties of kitten muscles. J. Physiol. 192:815-822.

Close, R. (1969). Dynamic properties of fast and slow skeletal muscles of the rat after nerve cross-union. J. Physiol. 204:331-346.

Close, R. I., (1972). Dynamic properties of mammalian skeletal muscles. Physiol. Rev. 52:129-197.

Coyle, E. F., D. L. Costill and G. R. Lesmes (1979). Leg extension power and muscle fiber composition. Med. Sci. Sports. 11:12-15.

Davies, C. T. M., and R. Rennie (1968). Human power output. Nature. 217:770-771.

Davies, C. T. M., and A. J. Sargeant (1975). Effects of exercise therapy on total and component tissue leg volumes of patients undergoing rehabilitation from lower-limb injury. Ann. Hum. Biol. 2:327-337.

Dawson, J., D. G. Gadian and D. R. Wilkie (1978). Muscular fatigue investigated by phosphorus nuclear magnetic resonance. Nature. 274:861-866.

Dern, R. J., J. M. Levene and H. A . Blair (1947). Forces exerted at different velocities in human arm movements. Am. J. Physiol. 151:415-437.

Desmedt, J. E., and E. Godaux (1977). Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. J. Physiol. 264:673-693.

Desmedt, J. E., and E. Godaux (1977a). Fast motor units are not preferentially activated in rapid voluntary contractions in man. Nature. 267:717-719.

Desmedt, J. E., and E. Godaux (1979). Voluntary motor commands in human ballistic movements. Ann. Neurol. 5:415-421.

Dickinson, S. (1928). The dynamics of bicycle pedalling. Proc. Roy. Soc. B. 103:225-233.

Dickinson, S. (1929). The efficiency of bicycle-pedalling, as affected by speed and load. J. Physiol. 67:242-255.

di Prampero, P. E., M. Meyer, P. Ceretelli and J. Piiper (1981). Energy sources and mechanical efficiency of anaerobic work in dog gastrocnemius. Pflugers. Arch. 389:257-262.

Duffield, F. A., and J. MacDonald (1923). Relationship between speed and efficiency. J. Physiol. 58:13P.

Edwards, R. H. T., A. Young, G. P. Hosking and D. A. Jones (1977). Human skeletal muscle function: description of tests and normal values. Clin. Sci. Mol. Med. 52:283-290.

Edwards, R. H. T. (1980). Studies of muscular performance in normal and dystrophic subjects. Brit. Med. Bull. 36:159-164.

Essen, B., E. Jansson, J. Henricksson, A. W. Taylor and B. Saltin (1975). Metabolic characteristics of fiber types in human skeletal muscle. Acta. Physiol. Scand. 95:153-165.

Faulkner, J. A., D. A. Jones, J. M. Round and R. H. T. Edwards. Dynamics of energetic processes in human muscle. IN: Ceretelli, P., and B. J. Whipp, Eds., Exercise Bioenergetics and Gas Exchange. Elsevier/North-Holland Biomedical Press, 1980, pp. 81-90.

Fenn, W. O. (1923). A quantitative comparison between the energy liberated and the work performed by the isolated sartorius muscle of the frog. J. Physiol. 58:175-203.

Fenn, W. O. (1930). Work against gravity and work due to velocity changes in running. Am. J. Physiol. 93:433-462.

Fenn, W. O., and B. S. Marsh (1935). Muscular force at different speeds of shortening. J. Physiol. 85:277-297.

Fick, A. (1892). Neue Beitrage zur Kenntniss von der Warmeetwicklung im Muskel. Pflugers. Arch. 51:541-569. CITED BY Fenn, W. O. (1923). A quantitative comparison between the energy liberated and the work performed by the isolated sartorius muscle of the frog. J. Physiol. 58:175-203.

Fuchs, F., V. Reddy and F. N. Briggs (1970). The interaction of cations with the calcium binding-site of troponin. Biochem. Biophys. Acta. 221:407-409.

Furusawa, K., A. V. Hill and J. L. Parkinson (1927a). The dynamics of sprint running. Proc. Roy. Soc. B. 102:29-42.

Furusawa, K., A. V. Hill and J. L. Parkinson (1927b). The energy used in sprint running. Proc. Roy. Soc. B. 102:43-50.

Gaesser, G. A., and G. A. Brooks (1975). Muscular efficiency during steady rate exercise: effects of speed and work rate. J. Appl. Physiol. 38:1132-1139.

Garnett, R., and J. A. Stephens (1978). Changes in the recruitment threshold of motor units in human first dorsal interosseus muscle produced by skin stimulation. J. Physiol. 282:13-14P.

Garnett, R., and J. A. Stephens (1981). Changes in the recruitment threshold of motor units produced by cutaneous stimulation in man. J. Physiol. 311:463-473.

Gasser, H. S., and A. V. Hill (1924). The dynamics of muscular contraction. Proc. Roy. Soc. B. 96:398-437.

Gevers, W., and E. Dowdle (1963). The effect of pH on glycolysis in vitro. Clin. Sci. 25:343-349.

Gollnick, P. D., R. B. Armstrong, C. W. Saubert IV, K. Piehl and B. Saltin (1972). Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. J. Appl. Physiol. 33:312-319.

Gregor, R. J., V. R. Edgerton, J. J. Perrine, D. S. Campion and C. Debus (1979). Torque-velocity relationships and muscle fiber composition in elite female athletes. J. Appl. Physiol. 47:388-392.

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

Grimby, L., and J. Hannerz (1981). Flexibility of recruitment order of continuously and intermittently discharging motor units in voluntary contraction. IN: Desmedt, J. E., Ed., Motor Unit Types, Recruitment and Plasticity in Health and Disease. Prog. Clin. Neurophysiol. Vol. 9, Karger, Basel, 1981, p. 201-211.

Grimby, L., J. Hannerz, J. Borg and B. Hedman. Firing properties of single human motor units on maintained maximal voluntary effort. IN: Ciba Foundation Symposium 82., Human Muscle Fatigue: Physiological Mechanisms. Pitman Medical Ltd., London, 1981, p. 157-165.

Guth, L., and F. J. Samaha (1969). Qualitative differences between actomyosin ATPase of slow and fast mammalian muscle. Exp. Neurol. 25:138-152.

Haagmark, T., E. Jansson and T. Svane (1978). Cross-sectional area of the thigh muscle in man measured by computed tomography. Scand. J. Clin. Lab. Invest. 38:355-360.

Hartree, W., and A. V. Hill (1928). The factors determining the maximum work and the mechanical efficiency of muscle. Proc. Roy. Soc. B. 103:234-251.

Henderson, Y., and H. W. Haggard (1925). The maximum of human power and its fuel. Am. J. Physiol. 72:264-282.

Henneman, E., G. Somjen and D. O. Carpenter (1965). Functional significance of cell size in spinal motoneurons. J. Neurophysiol. 28:560-580.

Henneman, E., G. Somjen and D. O. Carpenter (1965a). Excitability and inhibitability of motoneurons of different sizes. J. Neurophysiol. 28:599-620.

Hermansen, L. Effect of metabolic changes on force generation in skeletal muscle during maximal exercise. IN: Ciba Foundation Symposium 82., Human Muscle Fatigue: Physiological Mechanisms. Pitman Medical Ltd., London, 1981, p. 75-82.

Hill, A. V. (1913). The absolute mechanical efficiency of the contraction of an isolated muscle. J. Physiol. 46:435-469.

Hill, A. V. (1922). The maximum work and mechanical efficiency of human muscles, and their most economical speed. J. Physiol. 56:19-30.

Hill, A. V. (1926). The laws of muscular motion: Croonian Lecture. Proc. Roy. Soc. B. 100:87-108.

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. Proc. Roy. Soc. B. 126:136-195.

Hill, A. V. (1939). The mechanical efficiency of frog's muscle. Proc. Roy. Soc. B. 127:434-451.

Hill, A. V. (1940). The dynamic constants of human muscle. Proc. Roy. Soc. B. 128:263-274.

Hill, A. V. (1949). The heat of activation and the heat of shortening in a muscle twitch. Proc. Roy. Soc. B. 136:195-211.

Hill, A. V. (1956). The design of muscles. Brit. Med. Bull. 12:165-166.

Hill, A. V. (1964a). The effect of load on the heat of shortening of muscle. Proc. Roy. Soc. B. 159:297-319.

Hill, A. V. (1964b). The variation of total heat production in a twitch with velocity of shortening. Proc. Roy. Soc. B. 159:596-606.

Hill, A. V. (1964c). The efficiency of mechanical power development during muscular shortening and its relation to load. Proc. Roy. Soc. B. 159:319-325.

Hill, A. V. First and Last Experiments in Muscle Mechanics. Cambridge, University Press, 1970.

Hislop, H. J., and J. J. Perrine (1967). The isokinetic concept of exercise. Phys. Ther. 47:114-117.

Hoes, M. J. A. J. M., R. A. Binkhorst, A. E. M. C. Smeekes-Kuyl and A. C. Vissers (1968). Measurement of forces exerted on pedal and crank during work on a bicycle ergometer at different loads. Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 26:33-42.

Hohorst, H. J. L-(+)-lactate determination with lactic dehydrogenase and D.P.N. IN: H. U. Bergmeyer (Ed.) Methods of Enzymatic Analysis. Academic Press, New York, 266, 1965.

Hounsfield, G. M. (1973). Computerized transverse axial scanning (tomography). Part I. Description of system. Brit. J. Radiol. 46:1016-1022.

Huxley, A. F. (1957). Muscle structure and theories of contraction. Progr. Biophys. Biophys. Chem. 7:257-318.

Ikai, M., and T. Fukunaga (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 26:26-32.

Ingemann-Hansen, T., and J. Halkjaer-Kristensen (1979). Force-velocity relationships in the human quadriceps muscles. Scand. J. Rehab. Med. 11:85-89.

Ivy, J. L., W. M. Sherman, J. M. Miller, B. D. Maxwell and D. L. Costill (1982). Relationship between muscle QO_2 and fatigue during repeated isokinetic contractions. J. Appl. Physiol. 53:470-474.

Jones, P. R. M., and J. Pearson (1969). Anthropometric determination of leg fat and muscle plus bone volumes in young male and female adults. J. Physiol. 204:63-64P.

Jones, N. L., J. R. Sutton, R. Taylor and C. J. Toews (1979). Effect of pH on cardiorespiratory and metabolic responses to exercise. J. Appl. Physiol. 43:959-964.

Jones, N. L., and E. J. M. Campbell. Clinical Exercise Testing, 2nd Ed. W. B. Saunders Company, Philadelphia, 1981.

Jordan, L., and E. G. Merrill (1979). Relative efficiency as a function of pedalling rate for racing cyclists. J. Physiol. 49-50P.

Karlsson, J. (1972). Lactate and phosphagen concentrations in working muscle of man. Acta. Physiol. Scand. (Suppl) 358.

Katz, B. (1939). The relation between force and speed in muscular contraction. J. Physiol. 96:45-64.

Komi, P. V. Measurement of the force-velocity relationship in human muscle under concentric and eccentric conditions. Medicine and Sport. Vol. 8, pp. 224-229, Karger, Basel, 1973.

Larsson, L., G. Grimby and J. Karlsson (1979). Muscle strength and speed of movement in relation to age and muscle morphology. J. Appl. Physiol. 46:451-456.

Levin, J., and J. Wyman (1927). Viscous elastic properties of muscle. Proc. Roy. Soc. B. 101:218-243.

Lupton, H. (1922). The relation between the external work produced and the time occupied in a single muscular contraction in man. J. Physiol. 57:68-75.

Lupton, H. (1923). An analysis of the effects of speed on the mechanical efficiency of human muscular movement. J. Physiol. 57:337-353.

Margaria, R., P. Ceretelli and F. Mangili (1964). Balance and kinetics of anaerobic energy release during strenuous exercise in man. J. Appl. Physiol. 19:623-628.

Margaria, R., P. Aghemo and E. Rovelli (1966). Measurement of muscular power (anaerobic) in man. J. Appl. Physiol. 21:1662-1664.

Moffroid, M., R. Whipple, J. Hofkosh, E. Lowman and H. Thistle (1969). A study of isokinetic exercise. Phys. Ther. 49:735-747.

Moulds, R. F. W., A. Young, D. A. Jones and R. H. T. Edwards (1977). A study of the contractility, biochemistry and morphology of an isolated preparation of human skeletal muscle. Clin. Sci. Mol. Med. 52:291-297.

Murray, D. A., E. Harrison and G. A. Wood (1982). Cybex II reliability and validity: an appraisal. Med. Sci. Sports Ex. 14:153.

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

Newsholme, E. A. (1978). Substrate cycles: their metabolic, energetic and thermic consequences in man. Biochem. Soc. Symp. 43:183-205.

Nilsson, J., P. Tesch and A. Thorstensson (1977). Fatigue and EMG of repeated fast voluntary contractions in man. Acta. Physiol. Scand. 101:194-198.

Nonweiler, T. (1958). The work production of man; studies on racing cyclists. J. Physiol. 141:8P.

Olds, K., C. M. Godfrey and P. Rosenrot (1981). Computer assisted isokinetic dynamometry: a calibration study. Proceedings of the 4th Annual Conference on Rehabilitation Engineering, Washington, D.C.

Osborne, A. E., G. L. Read and D. R. Wilkie (1975). Bicycle ergometer with direct readout of torque, speed and power. J. Physiol. 18-19P.

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

Pugh, L. G. C. E. (1974). The relation of oxygen intake and speed in competition cycling and comparative observations on the bicycle ergometer. J. Physiol. 241:795-808.

Ranvier, L. (1873). Proprietes et structures differentes des muscles rouges et des muscles blanc chez les lapins et chez les raies. Compt. Rend. 77:1030-1043. CITED BY Close, R. I. (1972). Dynamic properties of mammalian skeletal muscles. Physiol. Rev. 52:129-197.

Ritchie, J. M. (1954). The relation between force and velocity of shortening in rat muscle. J. Physiol. 123:633-639.

Sapega, A. A., J. A. Nicholas, D. Sokolow and A. Saraniti (1982). The nature of torque "overshoot" in Cybex isokinetic dynamometry. Med. Sci.Sports. Ex. 14:368-375.

Sargeant, A. J., E. Hoinville and A. Young (1981). Maximum leg force and power output during short-term dynamic exercise. J. Appl. Physiol. 51:1175-1182.

Seabury, J. J., W. C. Adams and M. R. Ramey (1977). Influence of pedalling rate and power output on energy expenditure during bicycle ergometry. Ergonomics. 20:491-498.

Soden, P. D., and B. A. Adeyefa (1979). Forces applied to a bicycle during normal cycling. J. Biomechanics 12:527-541.

Sonnenblick, E. H. (1962). Force-velocity relations in mammalian heart muscle. Am. J. Physiol. 202:931-939.

Thorstensson, A. (1976). Muscle strength, fiber types and enzyme activities in man. Acta Physiol. Scand. Suppl. 443.

Thorstensson, A., G. Grimby and J. Karlsson (1976). Force-velocity relations and fiber composition in human knee extensor muscles. J. Appl. Physiol. 40:12-16.

Thorstensson, A., and J. Karlsson (1976). Fatiguability and fiber composition of human skeletal muscle. Acta. Physiol. Scand. 98:318-322.

Tihanyi, J., P. Apor and G. Fekete (1982). Force-velocity power characteristics and fibre composition in human muscles. Eur. J. Appl. Physiol. 48:331-343.

Tornvall, G. (1963). Assessment of physical capabilities. Acta. Physiol. Scand. Suppl. 201.

Unna, P. J. H. (1946). Limits of effective human power. Nature. 158:560-561.

Wells, J. B. (1965). Comparison of mechanical properties between slow and fast mammalian muscles. J. Physiol. 178:252-269.

Whipp, B. J., and K. Wasserman (1969). Efficiency of muscular work. J. Appl. Physiol. 26:644-648.

Wickiewicz, T. L., V. R. Edgerton, R. R. Roy, J. Perrine and P. Powell (1982). Human leg architecture and force-velocity properties. Med. Sci. Sports Ex. 14:144.

Wilkie, D. R. (1950). The relation between force and velocity in human muscle. J. Physiol. 110:249-280.

Wilkie, D. R. (1956). The mechanical properties of muscle. Brit. Med. Bull. 12:177-182.

Wilkie, D. R. (1960). Man as a source of mechanical power. Ergonomics. 3:1-8.

Wilkie, D. R. (1960a). Thermodynamics and the interpretation of biological heat measurements. Prog. Biophys. Biophys. Chem. 10:260-298.

Wilkie, D. R. (1968). Heat work and phosphorylcreatine break-down in muscle. J. Physiol. 195:157-183.

Wilkie, D. R. (1974). The efficiency of muscular contraction. J. Mechanochem. Cell. Motility. 2:257-267.

Wilkie, D. R. Equations describing power input by humans as a function of duration of exercise. IN: Ceretelli, P., and B. J. Whipp, Eds., <u>Exercise Bioenergetics and Gas Exchange</u>. Elsevier/North-Holland Biomedical Press, 1980, p. 75-80.

Wilkie, D. R. Shortage of chemical fuel as a cause of fatigue: studies by nuclear magnetic resonance and bicycle ergometry. IN: <u>Ciba Foundation Symposium 82.</u>, <u>Human Muscle Fatigue: Physiological Mechanisms</u>. Pitman Medical Ltd., London, 1981, p. 102-114.

Winter, D. A., R. P. Wells and G. W. Orr (1981). Errors in the use of isokinetic dynamometers. Eur. J. Appl. Physiol. 46:397-408.

Woledge, R. C. (1968). The energetics of tortoise muscle. J. Physiol. 197:685-707.

Young, A., I. Hughes, P. Russell, M. J. Parker and P. J. R. Nichols (1980). Measurement of quadriceps muscle wasting by ultrasonography. Rheum. Rehab. 19:141-148.