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Validation of Single Maximal Effort Tests for Power Measurement

by

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Dedication

I would like to dedicate this work to the following people:

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Often I heard you say, as if speaking in sleep, "He who works in marble, and finds the shape of his own soul in the stone, is nobler than he who ploughs the soil.

And he who seizes the rainbow to lay it on a cloth in the likeness of man, is more than he who makes the sandals for our feet."

But I say, not in sleep but in the over wakefulness of noontide, that the wind speaks not more sweetly to the giant oaks than to the least of all the blades of grass:

And he alone is great who turns the voice of the wind into a song made sweeter by his own loving.

From: The Prophet by -Kahlil Gibran-

Introduction

Sprint performance is determined to a large extent by the ability of an athlete to generate power. This is true for cycling, running, swimming, and speed skating events alike. The power output of a muscle, or muscle group, is the product of force and velocity:

$$P=fv \qquad \text{Equation 1}$$

Where P=power, f =force, and v=velocity

The maximal force that an individual is able to produce decreases as the velocity of muscle shortening increases. It was thought for many years that the relationship between reductions of maximal contraction force with increased contraction velocities was linear (Hill, 1922). In 1935 first Fenn and March and then A.V. Hill (1938) demonstrated that isolated muscles, and muscle systems, produce force and velocity according to a curvilinear relationship. The curvilinear, or linear force-velocity relationship, when combined with the equation for power (equation 1) dictates that there is a unique force of muscle contraction and a unique contraction velocity that will produce peak power. When studying muscles *in vitro* the unique force and velocity that allows peak power generation are referred to as the optimal force, and optimal velocity, and when studying movement *in vivo* are referred to as the optimal torque and optimal angular velocity.

The importance of power generation and its relationship to performance has lead to the development of numerous forms of power tests. More recently it has been demonstrated that multi-joint movements, like cycle ergometry, produce torque-velocity and power results that are analogous to the force-velocity & power measurements of isolated muscles (Hautier *et al.*, 1996; Buttelli *et al.*, 1996a). Measuring the force-velocity characteristics of cycle ergometry provides useful information to a coach or scientist which enables them to screen athletes for sprint or endurance performance potential, evaluate the effectiveness of a training program, and/or determine an individual's optimal cadence for power generation which may permit prediction of an athlete's muscle fibre type composition (Suter *et al.*, 1993). It is also of value to know the velocity that permits the highest power output so tests of power can be conducted under conditions that allow the individual to generate the highest power output.

The standard way of obtaining the force-velocity relationship with cycle ergometry is through multiple short sprint tests (5 seconds) with a variety of resistances (Vandewalle *et al.*, 1987).The force acting on the flywheel is a resistive load applied by a friction belt on to the flywheel; this load is measured with a weighted pendulum, or with strain gauge transducers. The force-velocity curve is then determined as each maximal achieved velocity is plotted against the respective resistance, and power is calculated with the following equation:

$$P = Rv \qquad \text{Equation 2}$$

Where R = resistance and v = velocity.

Using more technically advanced equipment, which can measure very small changes in flywheel velocity, allows the researcher to increase the accuracy of the power measure by including a calculation for work done against flywheel inertia.

$$P = I\alpha\varpi + Rv \qquad \text{Equation 3}$$

Where I = moment of inertia, α *= angular acceleration,* ϖ *= angular velocity, R = resistance and v = velocity.*

Using equation 3, power is calculated as a function of the applied resistance, acceleration, velocity, and moment of inertia of the flywheel. The multiple trials protocol, with and without calculations of moment of inertia, produces a force-velocity relationship that is roughly linear rather than hyperbolic (Hautier *et al.*, 1996; Seck *et al.*, 1995).

Peak power generation (and the corresponding torque and angular velocity) may be determined independently of frictional load using a cycle ergometer with no friction belt. This type of modified cycle ergometer uses either an increased moment of inertia of the flywheel or a high gear ratio (or a combination of both) to create a workload (Martin *et al.*, 1997). Inertia is described through the combination of Newton's 1^{st} and 2^{nd} laws of motion, and represents an object's tendency to remain still, or in constant motion. The flywheel on a cycle ergometer possesses a moment of inertia, which is a measure of the tendency of the flywheel to maintain its rotational velocity. To change the rate of rotation of a flywheel requires the application of a torque. A flywheel with a large moment of inertia will require a large torque to change its rotational velocity by a given increment, whereas a flywheel with a small moment of inertia will require the application of only a small torque to change its rotational velocity by the same increment. Martin et al. (1997) used the principle of inertial load to determine a torque-angular velocity relationship in a single maximal effort on a cycle ergometer. Martin et al. (1997) described inertial load with the following equation:

$$\textit{Inertial Load} = IG^2/2 \qquad \text{Equation 4}$$

Where I=inertia, G= gear ratio

By increasing the gear ratio, Martin et al. (1997) were able to create an inertial load that was great enough to enable the measurement of a subject's peak power in a single trial, with no frictional load. This finding seems to suggest that the power velocity curve, and torque-velocity characteristics, can be obtained from a single test, and multiple tests may be unnecessary (Martin *et al.*, 1997). However, the inertial load tests, though potentially useful, have not been directly compared with other cycle ergometry tests of power.

It is the primary goal of this study to determine if the single bout methods of determining the crank torque-angular velocity relationship for cycle ergometry (Martin *et al.*, 1997) are comparable with the traditional multiple trials methods

(Hautier *et al.*, 1996; Vandewalle *et al.*, 1987; Seck *et al.*, 1995)F for determination of the optimal conditions for peak power output.

Review of Literature

An individual's ability to generate power will vary according to their size, sex, age, training status, and of course the fibre type composition of their muscles. The desire to understand an individual's ability to generate power has spawned the development of many different forms of power tests. As power is a rate, the time frame that power generation is measured over, influences the values that will be obtained when effort is maximal. While power generation during the course of an activity is dependent upon many variables, peak power generation will occur at a specific combination of velocity of muscle shorting and load, that is fundamentally related to the fibre type composition and size of the active muscles (MacIntosh & Holash, 2000). As human motion is powered by muscular contraction, our ability to move and perform activities is also governed by these principles (Wilkie D. R., 1950; Vandewalle *et al.*, 1987). It is important to note though, that human movement involves the translation of the linear force and velocity of muscle contraction, to torques around joints and the angular velocity of limbs. As the torque and angular velocity of limb movement is fundamentally related to muscular contraction (Wilkie D. R., 1950; Tihanyi *et al.*, 1981) the optimal conditions for maximal power generation can be determined by recording the torque-angular velocity characteristics of the movement.

The focus of this study will be on the ability to accurately measure an individual's torque-angular velocity characteristics, and subsequent peak power generation, with cycle ergometry. The review of literature section has three subsections relating to this topic: (*i*) Skeletal Muscle Force-Velocity properties, (*ii*) Historical Perspectives on Measuring Power, and (*iii*) Application to Cycle Ergometry.

Skeletal Muscle Force-Velocity Properties

During concentric contraction, maximally activated skeletal muscle exhibits a characteristic relationship between the development of tension and the velocity of shortening. When activated maximally, a muscle will produce greatest force when the velocity of shortening is equal to zero. Conversely, a muscle will produce less force when the velocity of muscle shortening is greater. Fenn & Marsh (1935) first mathematically described the relationship between force development and shortening velocity. They plotted the maximal velocity of muscle shortening for a series of muscle contractions, each at a greater muscle load. The resulting relationship between force and velocity was a concave curve. Fenn & Marsh (1935) then formulated a mathematical exponential equation to describe the relationship. Further investigation by Hill (1938) indicated that the shape of the force-velocity curve appeared to be related to the way in which energy was released as the muscle shortened, from which he derived the *characteristic equation:*

$$(P+a)(v+b)=(P_o+a)b \qquad \text{Equation 5}$$

Where a=the shortening heat per cm. of shorting, b= the increase in energy rate per g. wt. decrease of load, v = the velocity of contraction P = the measured tension, and P_o *= the isometric tension*

Hill (1938) developed this equation first with isolated muscle fibres, and then proved it also applied to whole muscles *in vitro.*

Initially, Hill's characteristic relationship (Hill, 1938) was only demonstrated in experiments that used isolated muscles or muscle fibres *in vitro*, whereas experiments on intact muscles in the body produced linear force-velocity relationships (Perrine & Edgerton, 1978). In 1950, Wilkie demonstrated that the curvilinear relationship that was recorded in isolated muscle fibre contractions could also be found in intact muscle groups as they work in the human body, and the characteristic equation (equation 5) provided a suitable fit to the experimental data when ***a*** and ***b*** were treated as constants

Wilkie established 4 criteria for determining a suitable movement for measurement of the force-velocity relationship *in vivo*: 1) the joint should be geometrically simple, 2) the movement should involve few muscles, which in turn should have small tendon connections to the bone, 3) the movement should not disturb the rigid fixation of the body, and 4) the movement should be accurately reproducible (require little skill). From these criteria it was determined that a modified arm curl would suffice. Wilkie had his subjects sit down at the end of a table, rest their arm horizontally on the table and grab a handle connected to a wire cable so that their elbow was somewhat flexed at about 140°. The wire cable was attached to a lever that would lift a weight vertically at the other end of the table. When signalled, the subject pulled on the handle and contracted their biceps with maximal effort. Each subject performed a series of curls through a specific range of motion with various weights. The velocity of the movement was estimated from the charge accumulated on a condenser that reflected the time required to move through a given angular displacement. The results were corrected for inertia and the average velocity of contraction was plotted for each successive load. Wilkie found that in each case, once the values of *a* and *b* were determined, the Hill equation (equation 5) would suitably describe all the experimentally determined torque-angular velocity results.

Many years later, Tihanyi et al. (1982) demonstrated that it was possible to record results that fit the Hill Model (equation 5) in more complex muscle groups. Tihanyi et al. (1981) conducted a study to determine how muscle fibre composition affected the *in vivo* production of torque, angular velocity, and power of the large muscles of the leg. In addition to demonstrating that the characteristic torque-angular velocity curve could be found in more complex joints, Tihanyi (1981) found that the angular velocity at which peak power generation occurred (optimal angular velocity) was related to muscle fibre type. This study varied from other such studies (Gregor *et al.*, 1979) in that it used an after-load method to allow measurements at the highest muscle shortening velocities. Subjects were divided into two groups based on muscle fibre type as determined by biopsy of the vastus lateralus. The testing procedure placed subjects on their side to minimise the effects of gravity, and used a special dynamometer to measure torque generated around the knee during extension. Subjects performed a series of maximal contractions against various loads. Maximal angular velocity was determined for each successive load and plotted against torque. Mechanical power was then calculated from the equation:

$$P=T\varpi \qquad \text{Equation 6}$$

Where P = Power, T = Torque, and ϖ *= angular velocity*

This value was calculated at each successive load, and the maximal power was identified with respect to the angular velocity at which it was achieved.

Tihanyi (1981) demonstrated that the muscle fibre type composition of the legs was directly related to the ability of the individual to generate an angular velocity at any load, and to generate power. In their study (Tihanyi *et al.*, 1981) the individuals with the highest ratio of fast twitch fibres to slow twitch fibres, had not only the highest power generation but also produced peak power at the highest angular velocities. The discovery that muscle fibre type composition affects not only contraction velocities but also torque, and subsequent power generation, demonstrated the need to individually optimise load when attempting to determine peak power generation. Tihanyi's study provided two fundamental pieces of knowledge: i), that *in vivo* measurement of the large muscle groups of the upper leg could produce the characteristic torque-velocity relationship that was initially described by Hill (1938) and ii), that the optimal angular velocity at which peak power was produced, increased with increasing ratios of type II to type I muscle fibres.

Since the turn of the century there have been many investigations into skeletal muscle force-velocity characteristics. The key findings of these investigations have been: the force –velocity relationship is curvilinear, a curvilinear relationship can be found in maximally stimulated dissected muscle fibres and muscles (Hill, 1938), as well as, in mono-articular movements (Wilkie D. R., 1950; Tihanyi, et al. 1981). It has been also demonstrated that optimal conditions for power generation can be extracted from this data (Tihanyi *et al.*, 1981) and this is related to the muscle fibre composition. The importance of this latter point is that muscle or body size cannot be used to predict the conditions that permit the highest power output, since muscle fibre-type composition is independent of muscle size or body mass.

Historical Perspective on Measuring power

As discussed earlier, the ability to measure the conditions under which peak power generation occurs is essential in understanding and refining many types of athletic performance. The importance of evaluating power generation has resulted in the development of many forms of power tests. Essentially, these tests were designed to be simple so as not to involve too much skill, require a modest amount of equipment, and to be an honest representation of the individual's ability to generate power. Four classic tests for power that are represented in the literature are: isokinetic dynamometry (Suter *et al.*, 1993) stair climbing (Margaria *et al.*, 1966), vertical jump (Vandewalle *et al.*, 1987; Arsac et al. 1993), and cycle ergometry (Vandewalle *et al.*, 1987; Arsac *et al.*, 1996; Bar Or, 1987). These tests can be further subdivided into tests that use body weight for the load, (stair climbing and vertical jump), and body weight independent tests (Isokinetic dynamometry, and cycle ergometry). The variety of power tests is a testament not only to interest in power output, but also to the different conditions and situations where understanding power is important. The unique nature of each test as well as its applications and limitations, should be considered before selection of any power test.

Power tests, such as stair climbing and the vertical jump, are by far the simplest power tests to administer and calculate, as they depend solely on the individual's bodyweight and gravity to supply the load. Unfortunately, the reliance of stair climbing and vertical jumping test on bodyweight means that these tests are reflective of the subject's relative mass/body-stature as well as their ability to generate power. These tests can then be biased by such physical factors as height, body composition, and sex. However, tests such as cycle ergometry and isokinetic dynamometry are still relatively simple tests but can be manipulated so as to measure an individual's performance against a variety of imposed loads (cycle ergometry) or velocities (Vandewalle *et al.*, 1987; Baltzopoulos & Brodie, 1989) and are body weight independent. This flexibility not only permits the investigator to more accurately determine the individual's peak power output but also the optimal conditions for peak power output, so the highest possible peak power output is obtained.

While cycle ergometry and isokinetic dynamometry are more accurate measures of power, each test has its own unique strengths and weaknesses. Isokinetic dynamometry involves the rigid fixation of the body and isolates a single joint and muscle group for examination (Baltzopoulos & Brodie, 1989; Suter *et al.*, 1993) Subjects are directed to flex and extend their leg maximally against the lever arm. Angular velocity is restricted by an electric engine and is kept at a constant rate throughout the movement. Torque is measured from the strain of the lever arm. The greatest strength of isokinetic dynamometry is that it holds the body still and only measures the muscles around one joint. This will represent a very accurate action of the muscles *in vivo* (Baltzopoulos & Brodie, 1989; Suter *et al.*, 1993). Unfortunately, the greatest strength of isokinetic dynamometry is also its greatest weakness. The rigid fixation of the body and simple joint movement makes this test somewhat contrived. The movement does not directly correspond to movement during any sports event or daily living. Power output measures are therefore confined to the muscles that are involved directly and the power is not related to an actual movement like stair climbing, vertical jumping, and cycling. In comparison, cycle ergometry represents an actual sports movement (cycling) and is an indication of power generated at the foot by all the involved muscles in the leg (Vandewalle *et al.*, 1987; Bar Or, 1987). In cycle ergometry though, the multiple joint dynamic nature of the exercise limits the ability of the investigator to relate the results of the tests to the exact action of the muscles involved. In spite of this disadvantage, this test is generally useful and widely accepted.

Application to Cycle Ergometry

The Wingate test (the original cycle ergometry test of power) was designed to measure an individual's varying ability to generate power over 30 seconds. The test, developed in 1974 by Ayalon et al.(1974) at the Wingate Institute in Israel, used a standard cycle ergometer and required a subject to pedal maximally against a frictional load that was set proportional to body weight (75 grams/kg body weight) for 30 seconds. Subjects warmed-up for two minutes and then with 5 seconds left in the warm-up were given a count down and instructed to maximize their pedal rpm at the end of the 5 seconds. The predetermined load was added to the flywheel as quickly as possible and the subject kept pedalling at maximal effort for 30 seconds. Pedal revolutions were counted and power output was calculated, as a product of the resistive load on the flywheel and the corresponding average flywheel velocity. Power was then plotted against time from which maximal power, mean power, and magnitude of fatigue were determined. This test proved to be a simple, reliable, and easy to administer power test that could be performed with a minimum of technical equipment, and could be used on a wide spectrum of the population. Unfortunately, two problems have arisen with the standard protocol that question the overall validity of the test for measurement of power: 1, the use of a standard resistance proportional to body mass ($75g \cdot kg^{-1}$) does not provide optimal conditions for power output setting for all subjects, and 2) flywheel inertia is not taken into account, so the calculations of work and power ignore the varying amount of energy stored in the flywheel.

Prediction of a resistance setting for each subject that would elicit the highest possible peak power and mean power proved to be a difficult task. The original value of $75g \cdot kg^{-1}$ body weight used by Ayalon et al. (1974) was determined with untrained school age children, and was too low for most adults (Patton *et al.*, 1985; Dotan & Bar Or, 1983; Evans & Quinney, 1981). Dotan et al. (1983) tested both male and female physical education students and found gender must be taken into consideration when optimising frictional resistance. Dotan et al. (1983) determined that a resistance of $87g \cdot kg^{-1}$ was best on average for the adult males and that a resistance of $85g \cdot kg^{-1}$ was best on average for the adult females. Evans & Quinney (1981) tested adult varsity athletes and physical education students and found that optimisation of resistance based on a calculation of body weight was not very accurate and presented a calculation for resistance based on body weight and thigh volume. Evans and Quinney (1981) found that this formula resulted in an average resistance of $98g \cdot kg^{-1}$ for their test group. Patton et al. (1985) used the Evans and Quinney formula with a non-athletic group and found it to have low validity for determining the optimal resistance. Patton et al., (1985) found that a resistance of $94g \cdot kg^{-1}$ was best suited to producing peak power. Later in 1987, Bar-Or reviewed the research on the Wingate anaerobic test and determined that the force needed to determine the highest peak power in a Wingate test was higher than the force needed to determine the highest mean power. Bar-Or (1987) concludes the review with a statement that data collected on children with a disability shows that optimal force based on body size is meaningless, and that more data needs to be compiled to determine an appropriate manner of estimating optimal values for people of different ages, genders, training states, and body compositions.

The composition of an individual's muscles, gender, training status, and the effect of skeletal size on the orientation and relative length of levers formed as the muscles cross the joints, are factors that have been singled out as key in the development of power (Kautz *et al.*, 1991; Vandewalle *et al.*, 1987; Dotan & Bar Or, 1983). The majority of the investigations into optimisation of load in cycle ergometry have demonstrated the variability of optimal load between groups and individuals. This tends to suggest that the optimal conditions for peak power generation are best determined on an individual basis, taking into consideration the torque-angular velocity properties of the subject, rather than predicting the optimal resistance based on the body mass, or training condition of a group. While research by Dotan & Bar Or (1983) and Evans & Quinney (1981) has demonstrated that training status of the individual and skeletal size are important factors in determining an optimal resistance for peak power generation, research by Hautier et al. (1996) showed that optimal angular velocity is related to the fibre type composition of the involved muscles. The fact that several parameters affect an individual's ability to generate power, such as their age, stature, training status and fibre type composition of the involved muscles, dictates that an individual's peak power can only be measured accurately when resistance (and/or angular velocity) on the cycle ergometer is optimised for the individual.

In cycle ergometry power output depends on torque and angular velocity. If there is a specific relationship between torque and angular velocity for cycling, that is similar to the skeletal muscle force-velocity relationship, then there will be a unique combination of torque and angular velocity that will permit peak power output. The application of specific muscular principles to cycle ergometry requires the primary assumption that the torque that is measured at the flywheel represents the true action of the muscles of the leg. As the force-velocity properties of muscle are primarily responsible for determining optimal conditions for power output, it is assumed that these characteristics will be accurately represented in the action of the flywheel.

Vandewalle et al.(1987) addressed the problem of determining optimal conditions for peak power output in cycle ergometry with a different approach. Instead of trying to determine one normalised value that might elicit peak power for a whole group of subjects, peak power output was determined by conducting multiple short sprint tests (5 seconds), for which each successive sprint, flywheel resistance was increased. Optimal resistance was then determined as the resistance where an individual achieved his or her highest (Hill, 1922; Hill, 1938) power output. This method of determining optimal resistance for peak power output was based on the same basic principles that were used to determine the force-velocity relationship for isolated muscle *in vitro* (Hill 1938) and the torque-angular velocity characteristics of limb motion *in viv* (Wilkie D. R., 1950; Kautz *et al.*, 1991).

The transition to cycle ergometry as a testing platform involving the force-velocity characteristic was a significant step as it violated 3 of the 4 criteria that Wilkie (1950) established for measuring torque-angular velocity relationships *in vivo*; the joint was not geometrically simple, the movement involved many muscles, and the body was never rigidly fixed. It should be noted though, that while Vandewalle (1987) refers in his study to the "force-velocity relationship" he never measures, or claims to measure, the actual properties of the active muscles in the legs. Instead he measures the angular velocity of the cranks and the resistance applied to the flywheel. So as not to be confused with the force-velocity characteristics of an isolated muscle as described by Hill (1938) when Vandewalle (1987) refers to the force acting on the flywheel and the velocity of the pedals when acted upon by the muscles of the leg, it is better to refer to Vandewalle's "force-velocity characteristics" as torque-angular velocity characteristics for cycling.

In their study Vandewalle et al. (1987) had subjects perform a series of short 5 seconds sprints, interspaced with 5-minutes rest. The initial resistance on the flywheel was set quite low and was increased for each subsequent sprint until the subject could no longer attain a pedalling velocity of 100 rpm. Initial resistive load on the flywheel and subsequent increases, were determined as a function of the subject's age, and sex. The individual's torque-angular velocity curve was then determined as each maximal velocity of the flywheel was plotted against the corresponding resistive force and a line was fit to the data with linear regression. Power was then plotted as the product of the maximal achieved velocity and corresponding resistance, and peak power was found at the top of the resulting parabolic power curve. Vandewalle et al. (1987) found that from the athletes that he tested, the ones involved in power and speed sports had the highest power outputs at the highest optimal velocities. Vandewalle et al. (1987) also found that linear regression was a more appropriate fit to the data than a hyperbolic or exponential equation. It was also noted that there was a downward inflection (lower torque or velocity than expected) at the highest and lowest angular velocities.

While Vandewalle et al. (1987) was able to resolve the issue of optimisation of resistance by using multiple trials and determine individualised conditions for peak power much more accurately; he failed to account for the moment of inertia of the flywheel. Failing to account for the moment of inertia of the flywheel affected the results primarily in that the flywheel required an amount of work to accelerate it that was not being accounted for and it can be argued that since the test didn't account for this work it was not accurately measuring peak power generation and possibly not the velocity at which peak power would be achieved (Hautier *et al.*, 1996; Seck *et al.*, 1995).

It is generally accepted that the multiple short sprint test method of cycle ergometry represents the torque-angular velocity characteristic of the muscles of the lower leg (Hautier *et al.*, 1996; Vandewalle *et al.*, 1987; Seck *et al.*, 1995). The linear rather than hyperbolic nature of the torque-angular velocity curve is generally explained as a characteristic of the cycle ergometry torque-angular velocity test (Seck *et al.*, 1995; Buttelli *et al.*, 1996b).

The fact that *in vivo* measures tend to produce torque-angular velocity relationships that are roughly linear (sometimes convex) rather than hyperbolic (Perrine & Edgerton, 1978); (Arsac *et al.*, 1996; Vandewalle *et al.*, 1987; Seck *et al.*, 1995; Hautier et al. 1996) is a point which warrants some discussion. Different explanations for the linearity/convex nature of the torque-angular velocity relationship have been offered. Hill (1922) initially proposed that a linear relationship reflected the actual visco-elastic properties of muscle, but this was later disproved by Fenn & Marsh (1935) and then discarded by Hill (1938), after further research indicated that a hyperbolic model better described the force velocity relationship in isolated amphibian muscle. However, there are published reports of apparently linear force-velocity relationship for isolated mammalian muscles (Ameredes *et al.*, 1992).

In the discussion of his findings, Vandewalle et al. (1987) suggests that the hyperbolic relationship is not obtained because it was difficult to measure the full range of torque-angular velocity conditions, and that the dynamic nature of cycle ergometry makes it impossible to know the exact position, action, joint angle, and degree of activation, of all the muscles involved in the activity at the time peak angular velocity is achieved. While all of these arguments are valid, possibly the largest error was that Vandewalle et al. (1987) failed to calculate the moment of inertia of the flywheel and therefore did not account for torque that was required to initially accelerate the flywheel or the decrease in kinetic energy stored in the flywheel, which follows maximal velocity.

Considering moment of inertia when calculating torque-angular velocity characteristics is important (Hautier *et al.*, 1996; Seck *et al.*, 1995; Martin *et al.*, 1997), as the mass of most cycle ergometer flywheels is quite large. This large mass insures that the ergometer mimics as closely as possible the dynamics of riding a bicycle. The concept of accounting for inertia is not new and was recognised as early as 1922 when Hill used an inertia flywheel to try and determine the torque-angular velocity characteristics of the biceps muscles of the arm. Inertia is incorporated into the calculation of power in cycle ergometry by calculating power using equation 3.

The importance of correcting for inertia was also recognised by Wilkie (1950) Pertuzon and Lestiennne (1967) and by Perrine and Edgerton (1978) who also implicated its importance in being able to determine the actual hyperbolic nature of the torque-angular velocity relationship *in vivo.* The calculation of inertia in cycle ergometry is now common (Arsac *et al.,* 1996; Buttelli et al., 1996; Hautier et al., 1996, Martin et al., 1997; Capmal & Vandewalle 1996) and early omission of this in calculations can probably be deemed a result of a lack of technology to accurately obtain a continuous measure of flywheel angular velocity. However, this is a problem that persists, and it is quite likely that most of those who do not account for changes in the kinetic energy of the flywheel greatly underestimate the optimal angular velocity, and peak power, as a result.

Arsac et al. (996), who did account for flywheel inertia in their study, also reported a convex torque-angular velocity curve. Arsac et al. (1996) did not allow the use of toe clips to secure the subject's feet to the pedals, reasoning that the use of toe clips would allow the subjects to pull with the contralateral leg. To prove this point he retested some of his subjects with toe clips and found that with this adjustment, subjects now produced a linear torque-velocity relationship. Arsac concluded that the use of the contralateral leg is the only way in which subjects could generate torque at the cranks that exceed the torque produced by the weight of the body and the length of the crank and remain seated during the test. While convincing, this argument does not consider the stabilization that is provided by the arms pulling on the handlebars. It is possible that subjects had an increased security in foot placement that allowed them to push harder without fear of their feet slipping from the pedals.

Most recently, it has been demonstrated that peak power generation may be determined independent of frictional load (Martin *et al.*, 1997). This would mean that a single test could be used to determine the torque-angular velocity relationship without measurement of frictional resistance if the gear ratio (Martin *et al.*, 1997) or flywheel moment of inertia is increased (Arsac *et al.*, 1996). For the torque-angular velocity characteristics to be found in a single trial, subjects must start from a standstill, and initial load must be sufficient to generate accurate values for both; high torque/low angular velocity situations, as well as, situations of high angular velocity/ low torque. This finding seems to suggest that the power-angular velocity curve and torque-angular velocity characteristics can be obtained from a single test, and multiple tests may be unnecessary (Martin *et al.*, 1997).

In a study designed to measure maximal power in a single cycling bout (Martin *et al.*, 1997), an intermediate gear was used to increase the effective gear ratios and therefore prolong the time taken to accelerate the flywheel. Flywheel moment of inertia was very precisely calculated and flywheel displacement was continuously measured with a computer. Martin et al. (1997)concluded that maximal power could be determined in a single exercise bout lasting 3-4 seconds. While the values that were reported for muscular power (21.4 to 33.2 $W \cdot kg^{-1}$) were within the ranges that have been previously reported for other methods of determining power (Garhammer, 1991), Martin failed to compare the maximal power output values that were achieved with his methods with more established methods, namely the multiple trials test. Furthermore, although Martin et al. (1997) were able to generate a torque-angular velocity relationship, there is no reason to believe that the optimal conditions for a Wingate test could be obtained from this relationship. It may, however, be reasonable to anticipate that peak power output would occur at the same angular velocity whether determined by single or multiple trials.

Determination of torque-angular velocity characteristics and peak power with a single test requires three things: i), the ability to accurately measure very small changes in the velocity of the flywheel, ii) the ability to delay the acceleration of the flywheel so a sufficient number of muscular contractions can be performed before peak velocity is reached, and iii) accurate determination of the moment of inertia of the flywheel. Computer assisted data acquisition enables the measurement of flywheel velocity. The acceleration of the flywheel can be delayed by: increasing the gear ratio driving the flywheel, increasing the moment of inertia of the flywheel, adding resistance to the flywheel, or combinations of all three. Having a flywheel with a high moment of inertia, an increased gear ratio, or mild resistance, delay the acceleration of the flywheel by increasing the energy required to accelerate the flywheel at any point during the test and increases the number of pedal strokes that will be required before the legs reach their maximal pedalling rate. The torque produced at the cranks is then calculated through the equation

$$T=\alpha I \qquad \text{Equation 7}$$

Where T= torque, α=angular acceleration, and I= moment of inertia of the flywheel.

This method, however, only works for the "no resistance" conditions.

The ability to determine an individual's torque-angular velocity relationship from a single test is very desirable, especially if the resistive load or gearing does not need to be adjusted between subjects. Currently the process of determining the power & angular velocity relationships with multiple trials is very labour intensive for athletes and researchers alike. The involved nature of using multiple test trials as a method of determining the torque–angular velocity relationship has limited the use of this valuable method of assessing an athlete's ability. If a simple way to determine the torque-angular velocity relationship through a single trial could be validated it would provide an easier, less time consuming method of optimising conditions for the Wingate test.

Cycle ergometry is a very desirable method of measuring power, as it is a closely controlled test and is independent of body weight. With the use of computer data acquisition, cycle ergometry can generate a tremendous amount of data that can be used to: predict athletic performance, evaluate the effectiveness of a training program, provide an estimate of muscle fibre type composition, or calculate a cyclist's optimal cadence. Current advancements and refinements in cycle ergometry protocols tend to suggest that the standard multiple trial testing procedure for determining power might be replaced with single effort tests.

Purpose:

There were two purposes for this study:

To assess the validity of a single maximal effort test, in defining the torque-angular velocity properties of cycle ergometry. Multiple brief maximal efforts against various resistances were considered the "gold standard".

To determine whether an increased range of loads will produce a torque-angular velocity curve that is curvilinear rather than linear.

Hypotheses:

1) Peak power and the angular velocity at which peak power is attained will be the same whether determined in: a single test using a high moment of inertia flywheel, a single test where acceleration of a normal flywheel is delayed by increasing the gear ratio, a single test using light resistance and compensating for moment of inertia or, multiple trials test with a variety of frictional loads:

H_0: $H_1=H_2=H_3=H_4$.

2) A curvilinear (hyperbolic) crank torque-angular velocity relationship will be evident when a sufficient range of values for crank cadence is obtained.

Methods

To accomplish the proposed goal of this project, it was necessary to design and manufacture a modified cycle ergometer that was used to perform both single maximal effort tests and traditional multiple trials with added resistance. This modified cycle ergometer was used for the estimation of the crank torque-angular velocity properties, and to test the validity of this approach to measurement of peak power in athletes.

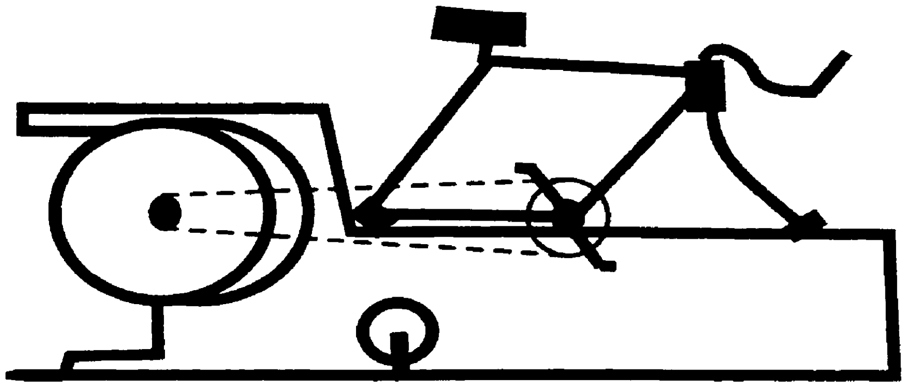
Design of the Cycle Ergometer:

A modified cycle ergometer was constructed with the assistance of the Engineering Machine Shop (Figure 1). The ergometer was built from a steel bike frame, mounted on a platform that was bolted to the floor for stability. The parts described below were attached to the platform. The advantage of using a steel bike frame for this project was that standard bike parts were used (cranks, pedals, seat, handlebars etc.). The modified cycle ergometer accommodated an extra gear (the swing link for this was welded to the platform) to permit tests with a high (double the normal) gear ratio, according to the design of Martin et al. (1997). The modified ergometer also accommodated a second flywheel that could be engaged or not. This second flywheel was synchronised with the first flywheel by a direct drive (engage or disengage the appropriate gear). The design of the ergometer permitted a selection of conditions varying from: i) standard ergometer (one flywheel with friction belt, driven by a gear ratio of 52/14); ii) a modified ergometer with one flywheel (no friction belt) with an increased gear ratio (52/7); and iii) a modified ergometer with two flywheels driven by the standard gear ratio (52/14).

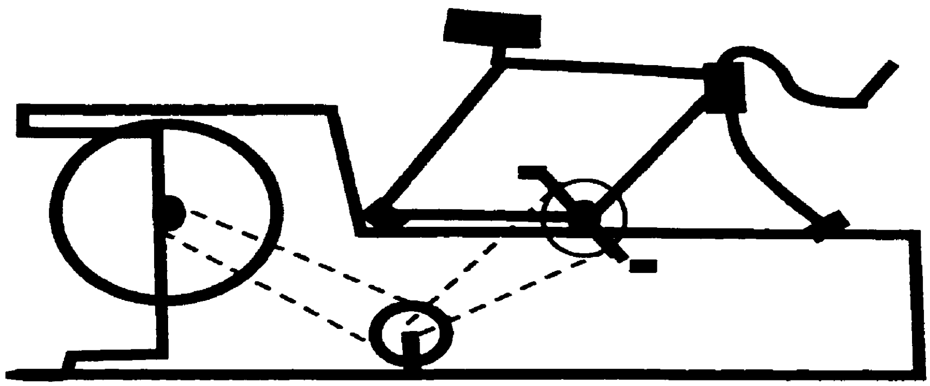
Data collection was accomplished with a Keithly Metrabyte DAS 1601 data collection card and a Pentium II 350 computer using the Easy-LX data collection program. Pedal revolutions were counted by placing 10 evenly spaced magnets along the inner chain ring and mounting a switch on the seat tube. When a magnet passed the switch there was an interruption of current flow. The interruptions in current flow were recorded with the data collection board. Interruption intervals occurred every 36 degrees of crank rotation. The time period over which these interruptions occurred were used to estimate crank velocity.

Resistance was measured with strain gauge transducers mounted on either end of the resistance belt (there was one belt only). These transducers were calibrated with static loads (known weights suspended from the transducers).

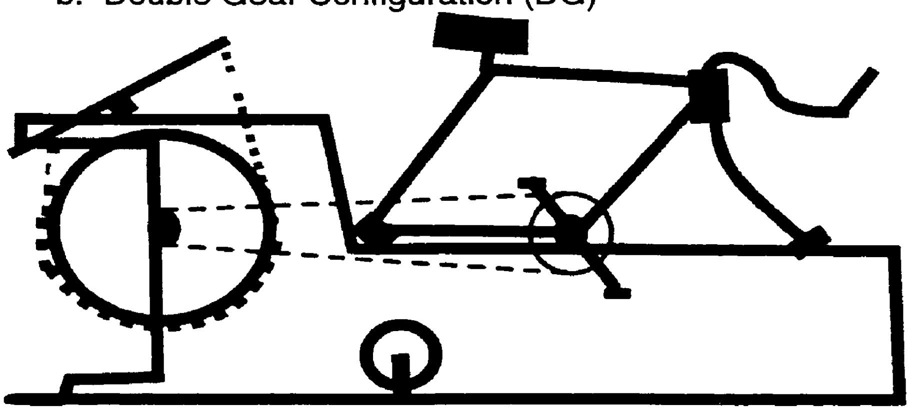
Velocity was measured with a banded disk mounted on the hub of the flywheel. A light detecting diode emitted a voltage spike each time a white section of the disk passed under it. The frequency of voltage spikes was proportional to the velocity, which was converted by the velocity meter to a voltage the magnitude of which was proportional to the frequency of voltage spikes. This voltage was calibrated and converted to velocity ($m \cdot s^{-1}$) by collecting data at several constant velocities of pedalling.



a. Double Flywheel Configuration (DF)



b. Double Gear Configuration (DG)



c. Multiple Trial and Light Resistance configuration (MT & LR)

Figure 1 Schematic of Cycle Ergometer.

The pedal switch was then used to calculate the actual velocity, and linear regression permitted an estimation of the velocity from any subsequent measurement from the velocity meter. Clipless pedals were used as opposed to toe clips as they were much more comfortable, provided better contact to the pedals than pedals with toe clips, and have replaced toe clips as standard equipment in cycling.

Experimental Design:

Subjects visited the Human Performance Laboratory twice; the order of these visits was randomised and separated by one week. On one visit torque-angular velocity data were collected using multiple trials method, which involved 6 repeated tests of increasing resistance. The three lowest resistance settings from the multiple trials test were then corrected for flywheel moment of inertia and used for the light resistance calculations. On the other visit torque angular-velocity data were collected using the double flywheel testing condition (single maximal effort with double the moment of inertia), and the double gear testing condition (single maximal effort with 52/7 gear ratio. Each of these single maximal effort tests was repeated three times and trials were separated by two minutes.

Subjects:

Two subject pools were used in this study: one group consisting of local track cyclists, and another group of active athletes and Kinesiology students. Male and female subjects from 20-35 years of age were studied. Twenty subjects (10 from each group) were recruited for the study. Criteria for inclusion into the elite group of the study included a minimum 2 years of competition in their sport and a minimum of 6 months of continuous training for their respective sport. Two subjects, one in each group, were female. Prospective subjects had the study explained to them, and were given a written description of the expectations of the study. All subjects signed an informed consent form as well as the Par-Q assessment (Appendix A). Any positive responses on the Par-Q resulted in exclusion from the study. Only 17 subjects successfully completed all tests.

Procedures:

The order of visits (multiple resistances vs. single tests) was randomised by the flip of a coin for each subject. Individual trials within each visit were randomised by the toss of a dye; duplicate trials were used to establish reliability of the test.

Multiple Trials Tests.

Subjects were permitted five minutes of warm-up at 100 -150 watts power output on a standard cycle ergometer. Within two to three minutes of ending the warm-up, the testing was initiated. Each trial consisted of 5 seconds of maximal effort against a fixed resistance beginning from a standstill. Trials consisted of a random variety of resistances that were selected to provide points on the torque-angular velocity curve with maximal crank angular velocities ranging from 45 rpm to 160 rpm. Two minutes of rest has recently been shown to be a sufficient rest period between all-out sprints in cycle ergometry (Buttelli *et al.*, 1996b) and this was therefore used as a rest period between trials. From this series of tests each subject's torque-angular velocity relationship was determined. This permitted the construction of the multiple trial torque-angular velocity relationship. A minimum of 6 trials were conducted to determine the multiple trials torque-angular velocity relationship. Trials ranged between 45 and 160 rpm were selected for linear regression and comparison to previous recorded results.

Increased Moment of Inertia and Increased Gear Load Trials

Subjects performed a total of six trials, three sequential trials for each of the two conditions: i) double flywheel, and ii) high gear ratio. The order of the conditions was randomised for each subject. Each trial was used to construct a full torque-angular velocity relationship. Changes in flywheel velocity were continuously recorded. A simple computer program was written to find the maximal torque of each pedal stroke and the corresponding angular velocity (Figure 2)

Statistical Analysis

Descriptive statistics were used to present the results (mean, standard error of the mean, linear and non-linear regression analysis). Results from each of the four testing protocols (multiple trials and single effort tests) were fit to a straight line and/or a curvilinear equation. The dependent variables for this analysis were the slope and intercept of linear regression. This provided a repeatable estimate of the torque-angular velocity relationship. Analysis of variance (ANOVA) was used to evaluate whether or not peak power output, angular velocity at peak power output, and torque at peak power output, were different between the various methods of conducting the test. When the ANOVA indicated that significant differences were present, the Newman-Keuls post hoc test was used to determine which inter-group differences existed.

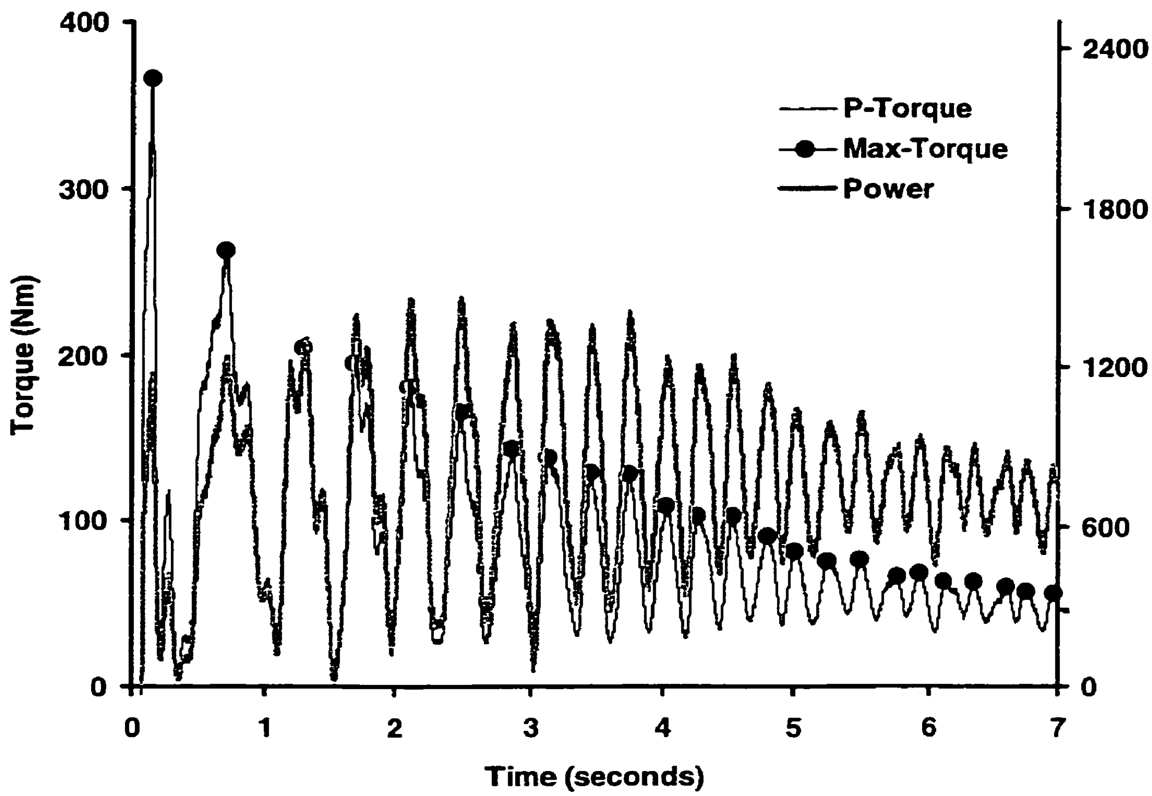


Figure 2. Recording from a Single Bout Trial

This figure shows continuous reading of Pedal Torque (P-Torque), Maximal Pedal Torque (Max-Torque) (equation 7), and Power (equation 6)

Results:

Subjects

Seventeen subjects reported to the lab for two testing sessions (15 males and 2 females). Their mean age and weight are presented in Table 1.

Table 1. Mean Subject Age & Weight.

Training Status	Number	Age (years)	Mass (Kg)
Kinesiology Students	7	27±3	73.6±3
Cyclists	10	28±3.	79.3±10.1
Combined	17	28±3	77.0±8.5

Velocity Calibration

Velocity calibration was performed in three steps: i) a range of frequencies that the velocity meter was able to convert to a corresponding voltage was determined (27-230 Hz), ii) A disk pattern was chosen that was anticipated to provide stable readings from 22-169 crank rpm. A disk with 22 dark bands was mounted to the flywheel, for single gear tests, and one with 11 dark bands was mounted to the flywheel for double gear tests, iii) Flywheel velocity was determined by having a subject ride the cycle ergometer at 6 different cadences. The average voltage output at each cadence was plotted against the actual velocity, determined from the pedal switch. Linear regression of this data yielded an equation that was entered into the EasyLx program for direct conversion of the sampled voltage into a velocity in $m \bullet s^{-1}$. A more detailed explanation of the velocity calibration is presented in appendix B.

Moment of Inertia

To determine the single flywheel moment of inertia, I used the spin down technique as described by Lakomy (1986) and Martin et al., (1997). A constant resistance was applied to the flywheel via a friction belt, and then the flywheel was accelerated to a velocity of approximately 450 rpm (equivalent to ≈ 100 rpm at the crank). It was then allowed to freely decelerate. This was repeated a total of 30 times at four different resistances. The rate of the flywheel deceleration ($rad \bullet s^{-2}$) was then plotted against the torque (Nm) acting on the flywheel, and linear regression was used to determine a line of best fit through all the data points. The moment of inertia of the flywheel is related to the torque applied by the friction belt and deceleration of the flywheel through the equation:

$$R + T_F = I \bullet \alpha \qquad \text{Equation 8}$$

Where R = Resistive torque created by the bearings and mechanical resistances within the cycle ergometer, T_F =torque applied by friction belt, I= inertia, and α= the angular acceleration.

Which can be transformed to:

$$T_F = I \bullet \alpha - R$$ Equation 9

Where symbols are defined as in equation 8.

This equation then becomes the equation for a straight line, where I is the slope and R is the intercept. I will equal the moment of inertia of the flywheel and R will equal the resistive torque created by bearings, axle and freewheel. For the single flywheel condition this resulted in a value of 0.8658 $Kg \bullet m^2$ for the moment inertia of the flywheel (appendix d). The moment of inertia of the double flywheel set-up was calculated in a similar fashion, with the exception that the flywheels were slaved together with a setscrew and the resistive belt was applied to only one of the flywheels. Eighteen trials were conducted at 4 different resistive loads. This test gave a moment of inertia value for the double flywheel set-up of 1.6119 $Kg \bullet m^2$ (appendix E).

Inertial Load

To calculate the workload imposed by a particular moment of inertia, gear ratio, or combination, Martin et al. (1997) used the concept of inertial load. This concept relates the inertial load to the kinetic energy required to change the velocity of the flywheel and is as follows:

$$KE = I\omega^2/2$$ Equation 10

Where KE = angular kinetic energy, I = moment of inertia and ϖ = angular velocity.

$IL=I(gear\text{-}ratio)^2/2$ Equation 11

Where *IL* stands for inertial load and *I* is equal to flywheel moment of inertia

Using this equation it was determined that the inertial load of the DG condition was 23.65 kg•m^2. The inertial load of the DF condition was 11.12 kg•m^2, and the inertial load of the LR condition (ignoring the resistance imposed) was 5.97 kg•m^2.

Test Reliability

All testing procedures resulted in torque-angular velocity data that displayed a linear relationship. When linear regression was used to determine a line of best fit through the data the mean R^2 of the line was >0.9 for all single trial testing conditions (DG, DF, LR). The mean R^2 for the line of best fit was >0.85 for the MT testing condition. The mean test retest correlation was R= 0.943 ± 0.02 (for single trial tests). The data sets from each testing condition were normally distributed (Appendix D). It is important to note that although 5 of the 17 subjects tested had torque-angular velocity relationships (in the single bout trials) that could also be viewed as concave curvilinear (Appendix C). A curvilinear equation was not used on these 5 subjects to determine the optimal conditions for power production. The purpose of fitting an equation through the data points was to interpolate the torque-angular velocity values between measured values. Using either a linear or curvilinear equation would not affect these values in a meaningful way so a linear equation (which adequately described all testing conditions) was used for all reported results. Once a line of best fit was determined from linear regression of the torque angular-velocity data, the line equation was used to determine the optimal conditions for developing peak power (optimal angular-velocity and optimal torque) see Figure 3.

The coefficient of variation (the standard deviation of the difference divided by the mean x 100) observed between tests was also very low: DG = 3%, DF = 2%, and LR = 2%.

Testing Protocols

A one-way analysis of variance showed that there were significant differences ($p<0.05$) in peak power, torque at peak power and velocity at peak power, between testing conditions MT, DF, DG, and LR. The omnibus hypothesis was rejected $H_0 = H_1 \neq H_2 \neq H_3 \neq H_4$ at $\alpha = 0.05$. A Newman Keuls post hoc test was used to reveal differences that existed between the means for each testing condition. These differences are illustrated in Figures 4a, 4b, 4c.

Subjects produced the highest mean peak power values under the DF and LR testing protocols. The DG protocol resulted in slightly lower mean peak power, and the MT testing condition gave the lowest mean peak power output. Post hoc analysis revealed that the mean peak power produced under the MT and DG testing conditions were significantly different than the other protocols and each other. A comparison of these values is presented in Figure 4a.

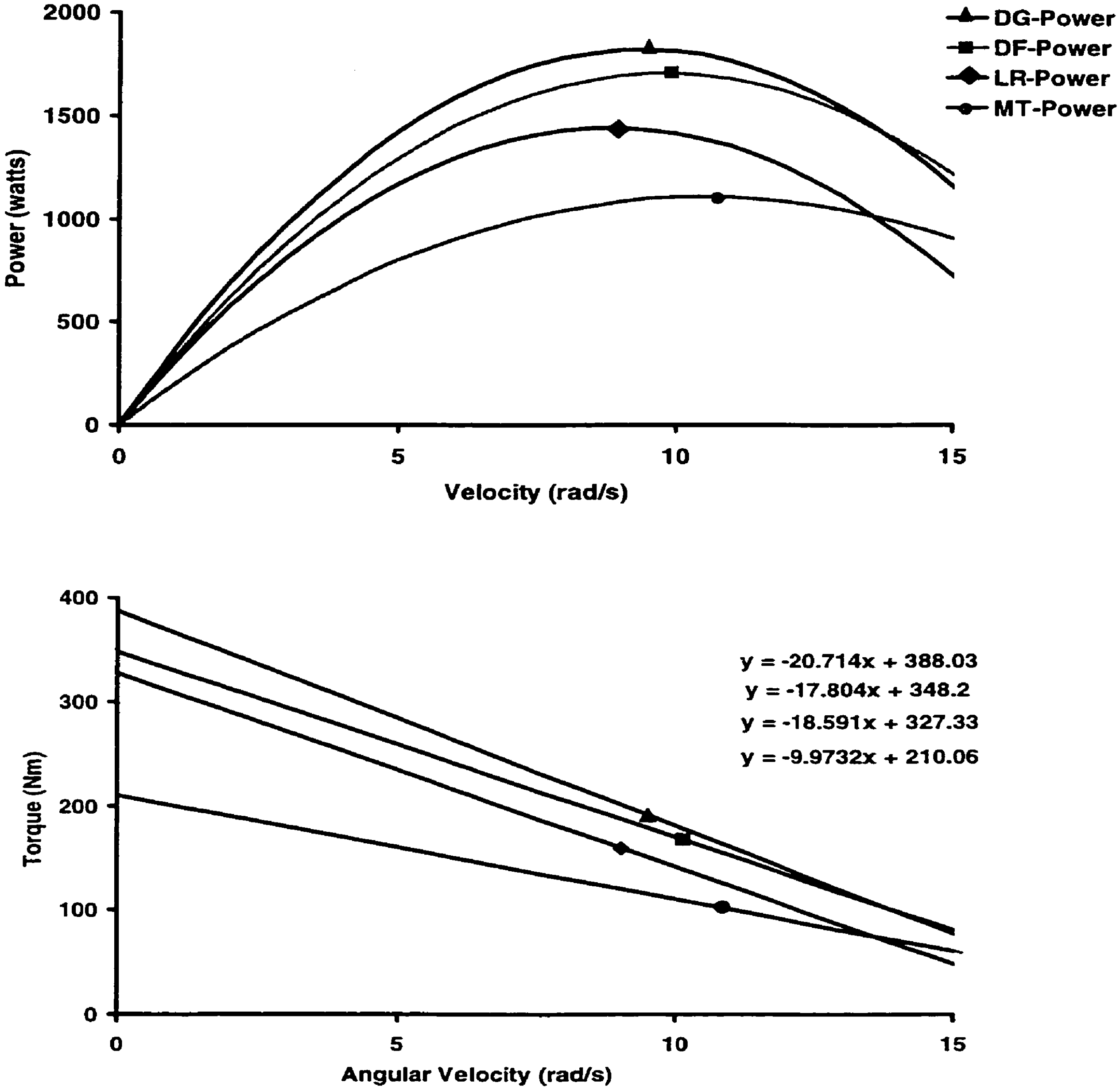


Figure 3. Sample Regression of Power and Torque vs. Angular Velocity

This figure is an example of the regression lines determined for one subject (subject 16) by each of the testing conditions. Symbols on the graphs represent peak power (upper) and corresponding optimal conditions for peak power output (lower).

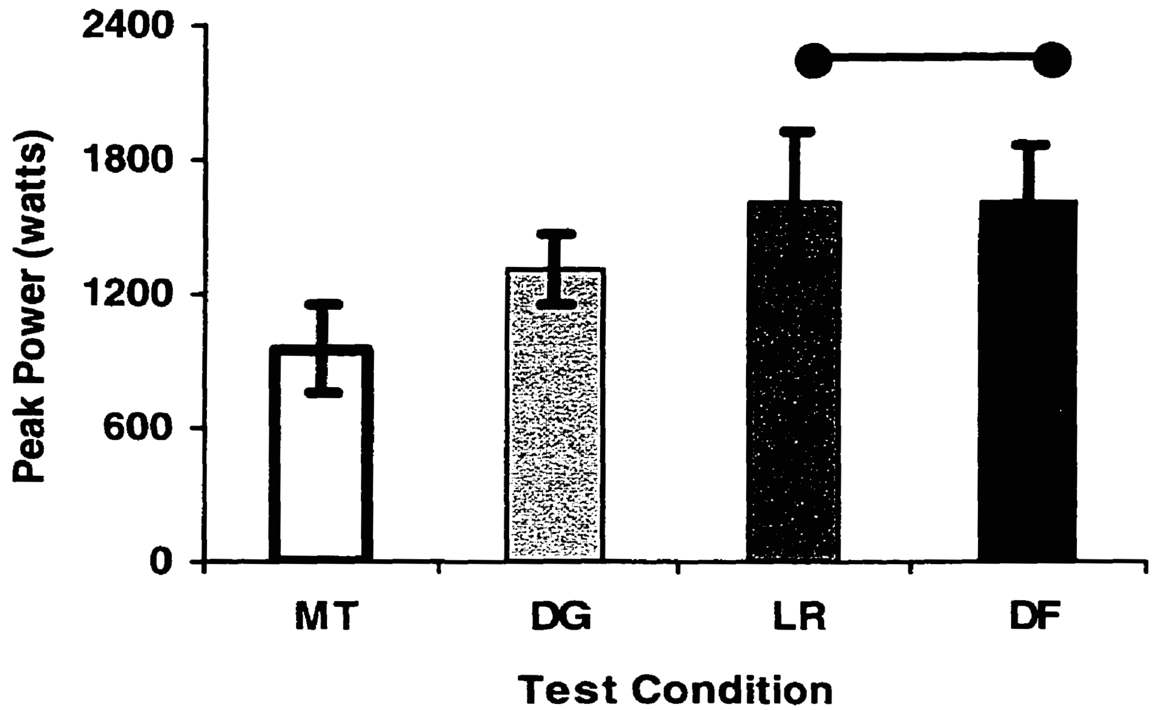
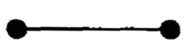


Figure 4a. Peak power

Figure 4. Comparison of Mean Peak Power from each Test Condition.

 Joined bar symbols join groups that were shown to not significantly differ with post hoc analysis, $\alpha = 0.05$. Testing conditions are MT (Multiple Trials), DG (Double Gear), LR (Light Resistance), and DF (Double Flywheel).

Optimal angular velocity and optimal torque were determined after linear regression was used to determine a line of best fit from the data as in the example in Figure 3.

Optimal angular velocity was the greatest in the LR testing condition followed by the MT, DF and DG conditions in decreasing order. Post hoc statistical analysis revealed that DG was significantly different from LR ($P < 0.05$). A graph illustrating these values is presented in Figure 4b.

Mean Optimal Torque was the highest under the DF testing condition, followed by the LR, DG, and MT testing conditions. Post hoc analysis revealed that there were no significant differences between DF, LR, and DG testing conditions. The MT, as in the Peak Power results, was significantly different from all other testing protocols (Figure 4c).

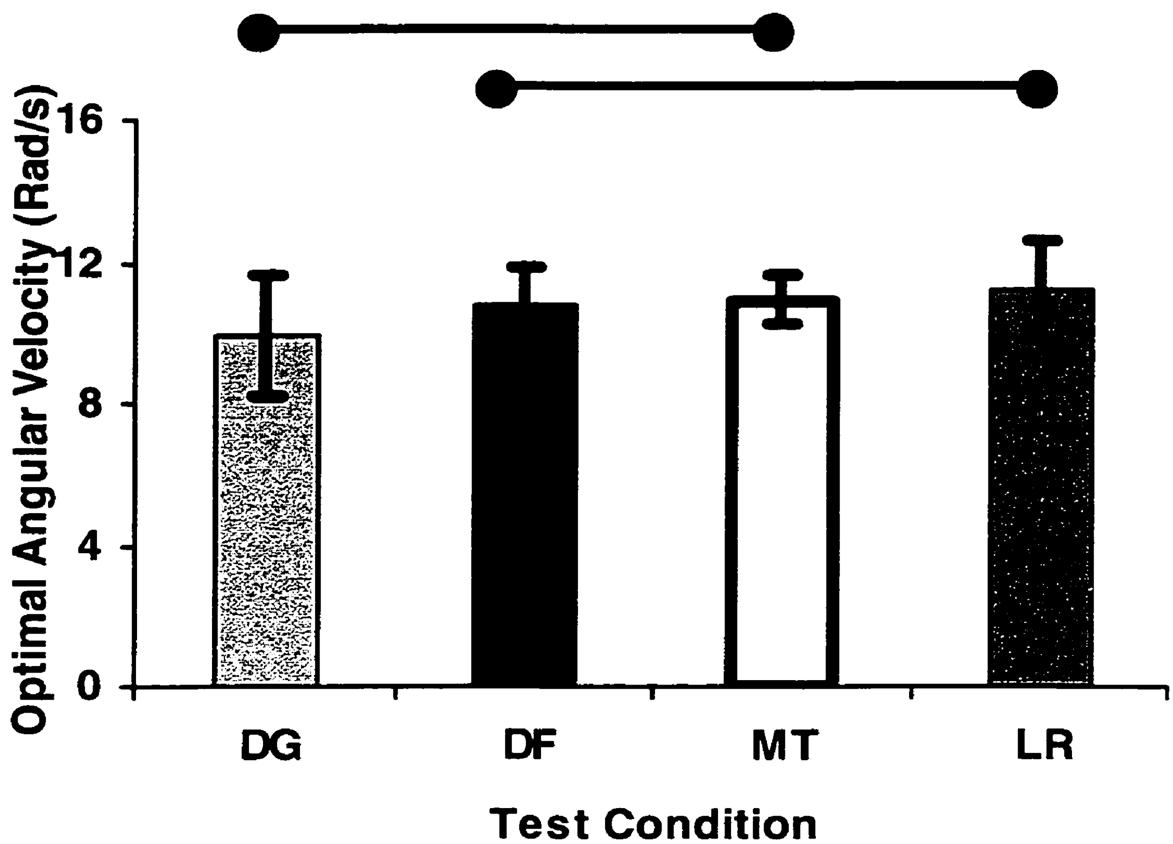


Figure 4b. Optimal Angular Velocity.

Comparison of optimal angular velocity for of peak power as obtained for each test condition. Post Hoc analysis revealed that there was a significant difference between groupings of DG, DF and MT or DF, MT, and LR. Testing conditions are as defined in Figure 4a.

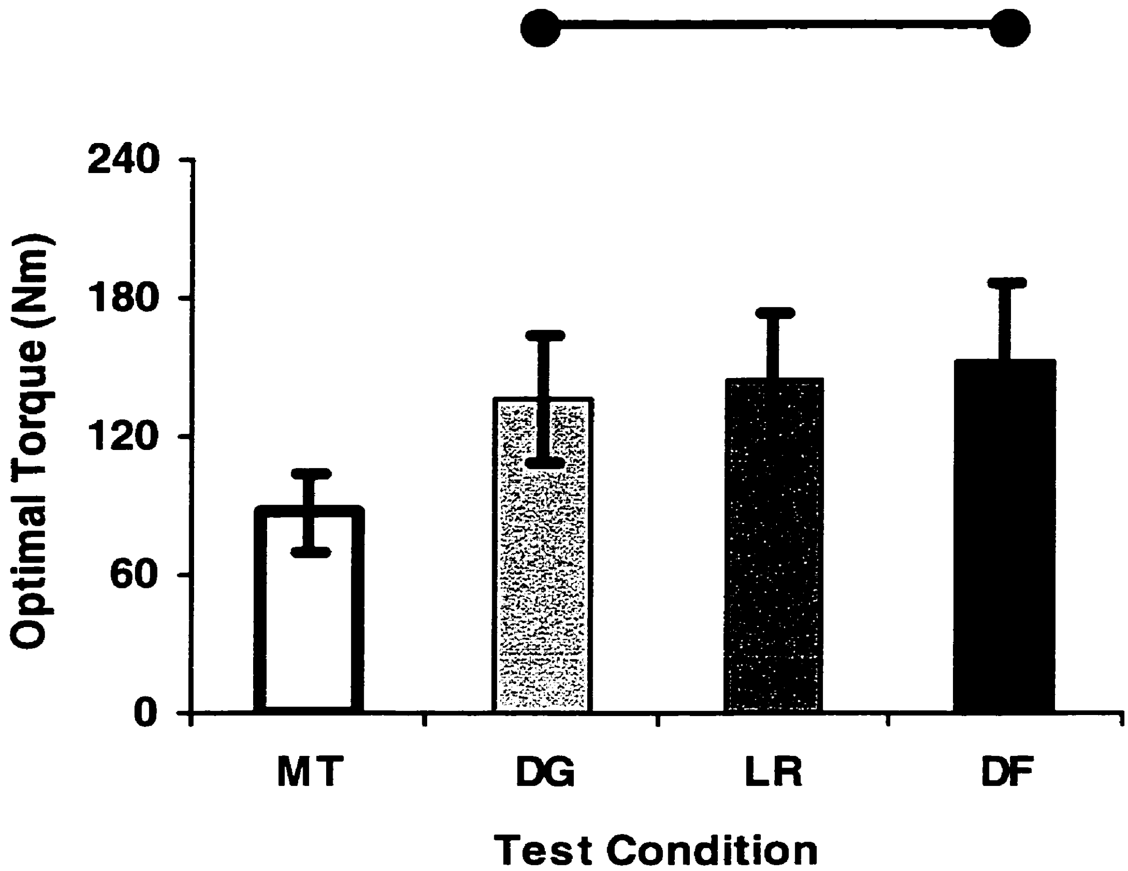


Figure 4c. Optimal Torque

Comparison of optimal torque for peak power as obtained with each test condition. The optimal torque for the MT test was significantly different from each other testing condition at P< 0.05. Test conditions are as described in 4a.

Time to Peak Power & Fatigue

The longer it took a subject to reach peak power output the lower their peak power was. This was apparent when the peak power in the single trial conditions, were compared (Figure 5). Mean results for optimal torque, optimal angular velocity, and peak power, along with time taken to reach peak power are presented in Table 2.

Comparison between Cyclists and Kinesiology Students

Cyclists produced greater peak power at a higher optimal torque (Figure 6), but the Kinesiology students had higher optimal angular velocity, although the extent and magnitude were recorded differently by each testing protocol (Table 3). Independent T-tests revealed that the DF condition yielded no significant differences in the peak power and optimal torque, and only nearly significant differences in optimal angular velocity ($P=0.051$) for cyclists' versus Kinesiology students. The DG testing protocol however, showed a significant difference in optimal angular velocity $P<0.05$ and optimal torque $P<0.01$ between cyclists and Kinesiology students, the LR testing protocol revealed a significant difference in optimal torque $P<0.05$ between cyclists and Kinesiology students, and the MT protocol showed significant differences in the peak power and optimal torque between cyclists and Kinesiology students (Table 3).

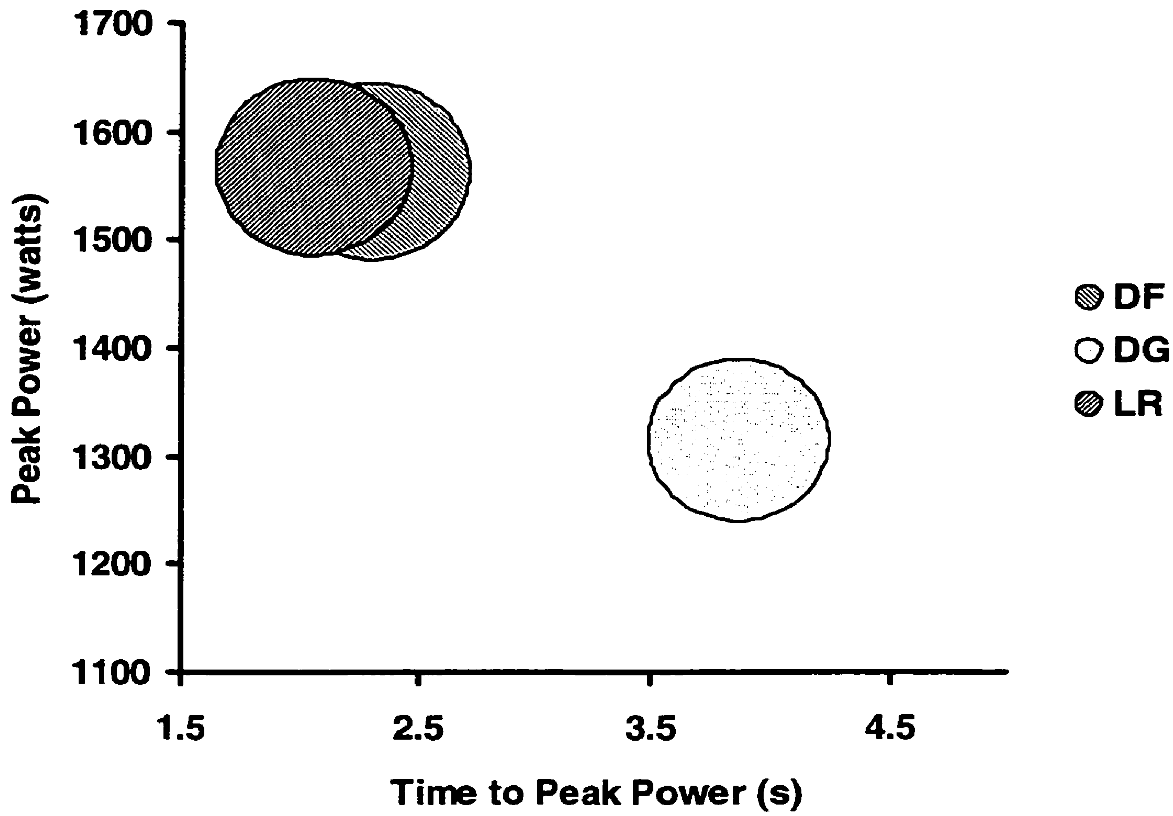


Figure 5 Power vs. Time to Peak Power

When Peak Power was reached at an earlier time Peak Power was higher. Bubble size represents peak power.

Table 2 Mean Values for Power and Optimal Conditions

Test Condition	Peak Power (watts)	Optimal Angular Velocity (rad/s)	Optimal Torque (Nm)	Time to Peak Power (seconds)
DG	1313 ± 160	9.93±1.75	136.07±27.53	3.86±1.07
DF	1562 ± 175	10.73±1.06	147.82±27.25	2.3±0.74
LR	1567 ± 259	10.98±1.05	141.83±25.67	2.06±0.39
MT	921 ± 194	10.89±0.71	84.71±16.85	NA
Avg	1341 ± 324	10.63±1.247	127.61±34.62	2.74±1.12

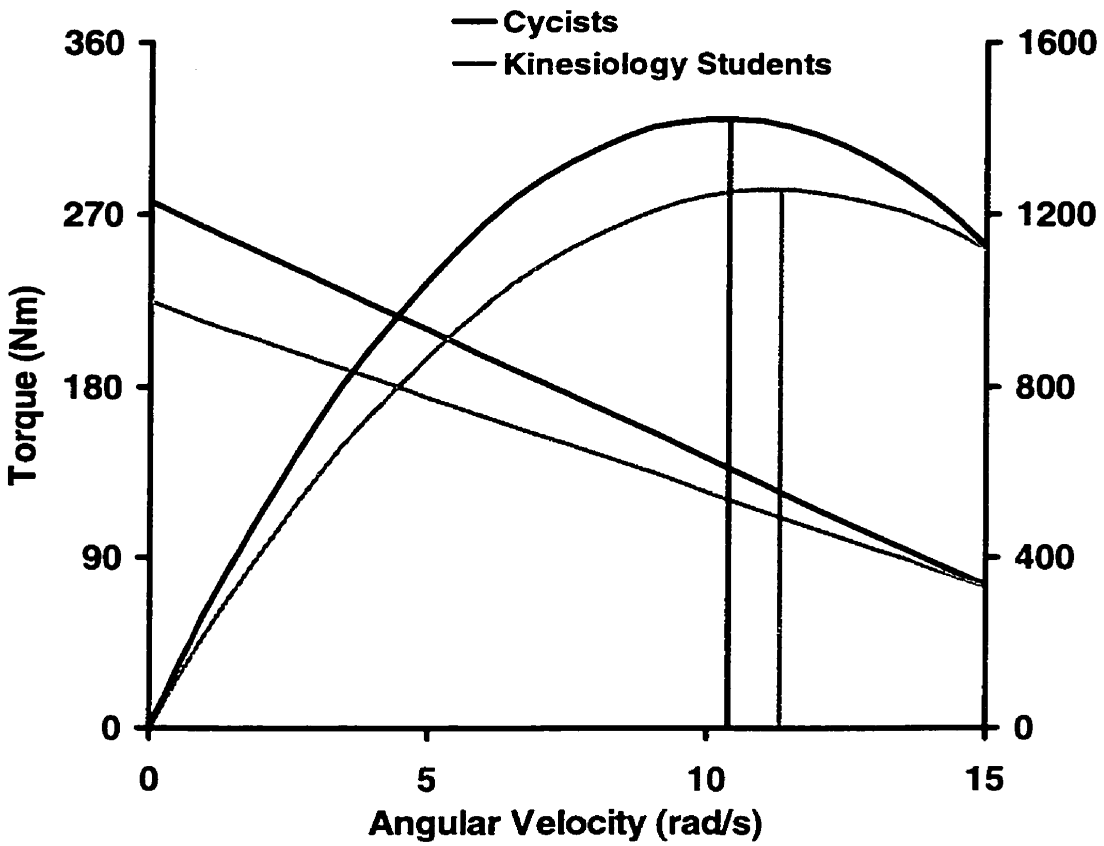


Figure 6 Optimal Conditions for Cyclists and Kinesiology students.

Linear torque angular velocity relationship for all-out cycling from all test conditions combined (DF, DG, LR, MT) for Cyclists and Kinesiology students. Vertical lines drop from peak power to intersect torque velocity lines at the optimal torque and optimal angular velocity. Optimal angular velocity, optimal torque, and peak power values are significantly different at $P<0.05$).

Table 3 Statistical Comparison of Cyclists and Kinesiology Students as Determined by Independent t-tests.

Test Condition	Peak Power	Optimal Velocity	Optimal Torque
DF	P=0.178	P=0.051	P=0.085
DG	P=0.171	P=0.03 *	P=0.007 *
LR	P=0.085	P=0.139	P=0.028 *
MT	P=0.017*	P=0.828	P=0.018 *

(*Significantly different at P<0.05)

Discussion:

There were two purposes of this study, the first was to assess the validity of a single maximal effort test in defining the torque-angular velocity properties of cycle ergometry, the second was to see if an increased range of loads would produce a torque-angular velocity curve that was curvilinear rather than linear.

As testing progressed it was apparent that the MT test, which was considered as the "gold standard" in our study, differed significantly from every other testing condition with respect to peak power, and optimal torque. The MT test was only similar to DF and DG testing conditions with respect to optimal angular velocity. The implication of these results was that the amount of work performed in a cycle ergometry test in accelerating the flywheel is significant enough to prevent the direct comparison of tests that include this calculation and tests that do not.

The reliability and validity of these testing protocols requires elaboration. All calibration trials demonstrated very high R^2 values (> 0.995), which would confirm a high degree of both accuracy and reliability in the measurements of flywheel moment of inertia, changes in flywheel velocity, and the corresponding calculations of torque for every trial. The coefficient of variation results for this study (DG = 3%, DF = 2%, and LR = 2%) were similar to the coefficients of variations reported by Sargeant et al. 6% (1982), Coggan and Costill 5.3% (1991), and Martin et al., (1997) 3.3%. All testing conditions were also very repeatable as was demonstrated by the test - retest correlation of peak power (DG R = 0.91, DF R = 0.85, and LR R=0.95).

These tests are valid in that they accurately and reproducibly measure torque, angular velocity, and peak power. Multiple tests on the same subject will produce the same results. It is important to be cautious here though, as the different testing obtained different results for peak power, optimal torque, and optimal velocity (Table 2). Even if we exclude the MT testing protocol from our comparison, as it does not account for flywheel moment of inertia, there is a difference in peak power achieved under the DG testing procedure (Figure 4a) in comparison with the other tests. While accuracy and repeatability were demonstrated within each testing procedure, the lower peak power achieved with the DG procedure suggests that a different condition or conditions imposed by this testing procedure impaired the subjects' ability to produce peak power. This condition could be an increase in system friction, as a result of using an extra chain and drive gear, or could be a result of the increased inertial load.

The purpose of doing these tests is to determine the optimal conditions for peak power generation. Therefore, within this study only the LR and DF tests are the two measures most likely to be valid, as they recorded the highest power outputs (Figure 4a) and there was no difference between the two with respect to the optimal conditions (Figures 4b, c). To make a more general statement that these two tests are valid measures of the optimal conditions for power generation is something that has yet to be proven, as these two tests will have to be cross validated with other measures and endure more scrutiny and comparison.

The moment of inertia of the flywheel proved to be an important factor in the measurement of peak power, as well as the determination of optimal conditions for peak power development. The MT condition gave values for peak power that were from 646 watts to 392 watts lower than the other tests (Figure 4a; Table 2). These values indicate a significant difference in the way the MT test measures the work performed by the subject during the test. If acceleration was absent when the subject reached optimal velocity there would be no difference in the torque measured between tests that consider moment of inertia and tests that do not. This, however, is not the case. At all times during the maximal effort test, even at optimal velocity, there are small oscillations in the velocity of the flywheel that occur during each pedal stroke. These small changes in velocity mean acceleration occurs in every pedal stroke, and the work done to create this acceleration changes the amount of torque required and the power produced.

The only results that were similar between the MT test and the other testing protocols (LR and DF) were optimal angular velocity (Figure 4b). This makes sense though, as the maximal velocity was similar between LR, DF, and MT testing conditions (Figure 3) and the optimal angular velocity is equal to 50% of the maximal velocity. This study clearly demonstrates that the amount of work performed by the subject in accelerating the flywheel is substantial in tests that start from a standstill, and should be accounted for in testing situations that wish to accurately calculate the amount of work or power produced in a test.

The discouraging aspect of the large difference in measured optimal torque between the MT test and all other tests was that none of the single bout measures can be used to predict the optimal resistance for a Wingate test. The reason for this is that a steady angular velocity is never achieved. There are always small oscillations in the angular velocity within each pedal stroke. Therefore when flywheel inertia is accounted for, single bout trials (DF & LR) will yield the same torque-angular velocity relationship, whether or not resistance is applied (DF & LR in Figure 4b). In contrast, when moment of inertia is not accounted for, torque is underestimated at any angular velocity (MT trials).

Initially the high inertial load tests (DF & DG) seemed to be the perfect tests, as they require a minimal amount of set up, and measure torque and angular velocity over a very broad range of angular velocities. The tests work on the principle of a mechanical loop. In the course of a pedal stroke, torque generated at the crank results in acceleration of the flywheel; this in turn requires an increased angular velocity of the crank allowing a new torque-angular velocity measurement on a subsequent pedal stroke. This process continues with each consecutive pedal stroke. Using this model, increasing the moment of inertia of the flywheel would simply make the measurement more discrete, by reducing the acceleration of the flywheel for a given torque, and thus increasing the required number of pedal strokes a subject would make before maximal velocity was reached. Unfortunately, this model does not account for fatigue. Each effort produced at the cranks, requires the maximal contraction of many muscles within the leg, and the number of maximal contractions that can be performed before there is a decrease in torque at the cranks is limited.

When we consider only tests that take into account flywheel inertia, we see that the DG trial has a lower peak power. The observed difference in the peak power measured by the DG condition, can be related to either, testing load, test duration, loss to mechanical friction, or the combination / interaction of all three.

It was an initial goal of this study to replicate the testing protocols that were used by others (Hautier *et al.*, 1996; Arsac *et al.*, 1996; Martin *et al.*, 1997) namely the MT, LR, DF and DG conditions. Unfortunately, the steel flywheels that were used in this study had more than double the moment of inertia of the flywheel used by Martin et al. (1997) (0.8658 kgm^2 (single), 1.6119 kgm^2 (double) vs. 0.3962 kgm^2 (single)). The result of this was that the DG trial had an inertial load of 23.65 kgm^2, and the DF condition had an inertial load of 11.12 Kgm^2 (compared to a DG inertial load of 10.93 Kgm^2, Martin et al. 1997).

Martin et al. (1997) reported that pilot testing revealed that maximal power was stable across a range of inertial loads from 5.6 – 12.6 Kgm^2, if this is correct then the inertial load of our double gear test is clearly out of this range at 23.65 Kgm^2, but the inertial load of our DF and LR conditions are within this range at 11.12

Kgm^2 and 5.97 Kgm^2 respectively. The similarity in the reported mean values between LR and DF testing conditions, and the differences observed between these and the DG testing condition would tend to support the finding reported by Martin et al (1997).

The time taken to achieve peak power seems to also indicate whether the test will be an accurate measure of peak power or not. In the Martin (1997) and Arsac (1996) papers, the time to peak power is in the range of 1.8 ± .4 seconds. This was also within the range of the LR (2.06± 0.39 s) and DF (2.30± 0.74 s) trials (Table 2 or Figure 5) while the time taken to reach peak power in the DG trial was nearly double these values (3.87± 1.07 s). In Figure 5, it is clear that the general trend is, the longer it takes to achieve peak power the lower the power will be. These results are similar to findings of others (Bar Or, 1987; Patton *et al.*, 1985; Gregor *et al.*, 1979) . These authors found that if resistance was set too high and it took longer than 5 seconds to reach peak power then peak power will be underestimated.

The time taken to achieve peak power may be related to fatigue. In Figure 5, the difference between the values obtained in the DG and the other single trial tests, is the uniform depression in the torque at a given velocity. These results are nearly identical to the depression in torque that was demonstrated by Buttelli et al. (1996). Buttelli et al. (1996) designed their study to measure the effect of fatigue in cycle ergometry. In this study Buttelli et al. (1996) measured the torque-angular velocity relationship in subjects before and after an exercise that was intended to fatigue the subjects. The slope of the torque-angular velocity relationship was similar pre and post fatigue, but fatigue resulted in a depression in torque at any angular velocity. This is exactly the same trend that was observed between DG and either DF or LR tests in this study (Figure 3). Buttelli (1996) cautiously hypothesised that this fatigue effect may be the result of localized fatigue of the fast twitch muscle fibres, as demonstrated in the depression of maximal torque as well as the apparent change in maximal angular velocity.

A mathematical model of mixed muscle presented by MacIntosh et al. (1993) would support this interpretation. The model predicts that when a greater proportion of the isometric force is generated by slow twitch motor units then optimal velocity will be slower. If there was any fatigue in the current tests, it would have been transient since two minute rest intervals are known to prevent cumulative fatigue (Blonc *et al.*, 1998). Furthermore, the testing order was randomised to prevent a systematic error due to cumulative fatigue. There is evidence in the results that argues against fatigue contributing to the low values for DG. If transient fatigue developed during a 4-5 second trial, peak torque would not be affected. This is because peak torque occurs early in the test (at low angular velocities). However this is not the case. It is possible that there was an additional resistance created by the extra gearing and chains. However, not all subjects produced less power under the DG testing condition; in fact the three strongest subjects produced more power in the DG trial than either the DF or LR trials. A full understanding of the limitations of the DG condition will require further research.

In this test we had two distinct groups as participants: track cyclists that had been competing for 2 years and training for at least 6 straight months, and active Kinesiology students. There was a general trend that cyclists had higher power outputs and higher optimal torque, while Kinesiology students had higher optimal angular velocities (Figure 6). Initially these results came as a surprise, as it was expected that the trained cyclists would exhibit both higher optimal angular velocities and higher optimal torques, similar to the findings of Tihanyi (1982) (assuming that track cyclists had higher proportions of FT fibres). Further investigation revealed that the linear torque angular velocity relationships of the cyclists and Kinesiology students tended to converge at 16 rad•sec^{-1} (Figure 6)(the maximal recorded angular velocity). This means the students would have a higher predicted maximal velocity, and therefore a higher optimal velocity.

In this study all testing conditions produced torque-angular velocity relationships that were linear in nature. It was hoped that the testing method utilized in this study would allow accurate measurement of crank velocities from 2.4 rad•s^{-1} to 20.6 rad•s^{-1}, and that this accuracy would reveal if the torque-angular velocity relationship were curvilinear. Unfortunately, in approximately 50% of the trials there was signal noise at either end of the velocity range in the single and multiple trial torque-angular velocity tests. In order to maintain comparability between all tests, all testing information below 5.1 rad•s^{-1} and above 16 rad•s^{-1} was not included in the results. This may have prevented clear accomplishment of the second goal of this research.

Five of the 17 subjects produced torque angular velocity relationships that were slightly concave curvilinear and 3 of the subjects produced torque-angular velocity relationships that were slightly convex curvilinear. However, fitting the data with either a convex or concave curve, did not improve the fit over that of a linear equation (Figure 9, appendix c). As a linear or curvilinear fit did not significantly improve the correlation, it seems unlikely that a curvilinear equation would predict the peak power better than a linear equation. The linear torque-angular velocity relationships observed in this study are similar to those that have been reported in other cycle ergometry studies (Hautier *et al.*, 1996; Arsac *et al.*, 1993; Martin *et al.*, 1997). As the torque-angular velocity curve in cycling is always recorded as a linear function, even in studies that succeed in measuring both the low and high velocities during cycling (Capmal & Vandewalle, 1997; Martin *et al.*, 1997) the linear torque-angular velocity relationship is most likely a characteristic of cycle ergometry.

Conclusions

1. The LR and DF conditions were very simple tests to administer and both testing conditions allowed subject to produce their highest power outputs.

Therefore, these were the best tests for measuring the optimal conditions for peak power output.

2. Cycle ergometry tests that use moment of inertia as the sole estimate of load, resulted in torque- angular velocity relationships and peak power values that are not directly comparable to results from tests that do not account for flywheel moment of inertia.

3. Inertial load could be large enough (i.e. the DG trial) to prevent the determination of optimal conditions for a cyclist's peak power. For single bout measures to be accurate inertial loads should be in the range of 5.6 – 12.6 kgm^2

4. Since the torque relates to angular velocity, independent of frictional resistance (DF & LR), tests that take into account moment of inertia cannot be used to predict optimal resistance for a Wingate tests.

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Appendix A

Informed Consent Forms

B.R. MacIntosh and R.J. Holash Consent Form (Phase I)

Project: Validation of Single Maximal Effort Tests for Power Measurement

Funding Agency: Sport Science Association of Alberta

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research project is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. A participation readiness questionnaire (Par-Q) is included in this package and must be read and completed before you can participate. Please take the time to read this carefully and to understand any accompanying information.

The purpose of this study is to assess the validity of a single maximal effort test, in defining the force velocity properties of cycle ergometry. Testing will take place at the Human Performance Laboratory (HPL) at the University of Calgary. Someone will contact you from the HPL and co-ordinate a time that is convenient for you.

A cycle ergometer is a stationary bike that measures the speed of the flywheel, the cyclist's cadence and resistance placed on the flywheel. You will be allowed five minutes of warm-up at 100 -150 watts power output on a standard cycle ergometer. Within three to five minutes of ending the warm-up, the first trial will be initiated. Each trial will consist of 5 s of maximal effort against a fixed resistance. The first resistance will be set according to body mass, and will be varied between trials. Five minutes of rest will be permitted between trials. Trials will start from a dead stop, and you will be given a count down of 5 seconds leading up to the start, and will be informed when the 5 seconds trial is over. If at any time you feel unable to comply with the testing protocol the test will stop.

The benefits of participating in this study include the opportunity to have your maximal cycling sprint power assessed and the force velocity characteristics of your muscles determined. The results of this pilot project will determine if this method is appropriate for future research. A of graph of your maximal power output will be given to you if you request, and an explanation of your results will be discussed with you. All data collected will remain confidential with regard to your identity. Data will be coded and any reference to your name will be destroyed upon completion of the project. To insure your safety all testing will be completed by a trained graduate student who is familiar with testing high performance athletes and the detailed safety procedures of the HPL

Your signature on this form indicates that you have understood, to your satisfaction, the information regarding your participation in this research project and agree to participate as a subject. In no way does this waive your legal rights, nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardising your relationship with the University of Calgary, or the Human Performance Laboratory in any way. The investigators reserve the right to terminate your participation in the project at any time.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification of any information throughout your participation. If you have further questions concerning matters related to his research please contact: John Holash: 220-4209 or Dr. Brian MacIntosh: 220-3431

If you have any questions concerning your rights as a possible participant in this research, please contact the office of the Vice President, Research at 220-5465, and ask for the Chairperson of the Committee of Ethics for Human Studies, at the University of Calgary

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Name (Please Print) Name of Witness (please print

______________________________ __/__/__ ______________________________ __/__/__

Signature Date Signature Date

Robert John Holash ______________________________ __/__/__

Name of Researcher Signature Date

Brian R. MacIntosh & R. John Holash: Consent Form (Phase II)

Project: Validation of Single Maximal Effort Tests for Power Measurement,

Funding Agency: Sport Science Association of Alberta.

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research project is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. A participation readiness questionnaire (Par-Q) is included in this package and must be read and completed before you can participate. Please take the time to read this carefully and to understand any accompanying information.

The purpose of this study is to assess the validity of a single maximal effort test, in defining the force velocity properties of cycle ergometry. Testing will take place at the Human Performance Laboratory (HPL) at the University of Calgary. Someone will contact you from the HPL and co-ordinate a time that is convenient for you. Each testing session should last approximately one hour.

A cycle ergometer is a stationary bike that measures the speed of the flywheel, the cyclist's cadence and resistance placed on the flywheel. You will be required to visit the lab on three separate occasions. In each case you will be given a five-minute warm-up followed by maximal effort trials. On one occasion, the cycle ergometer will be set up with a single flywheel, and a gear ratio of 52/14. You will be given no more than 8 trials with a variety of resistances, to permit construction of the multiple trial, force-velocity relationship. On another visit, you will be given six trials, two for each condition: i) double flywheel, ii) high gear ratio, and iii) low resistance. Each of these trials will be used to construct a full force-velocity relationship. If at any time you feel unable to comply with the testing protocol, or would like to stop, the test will stop. A third visit may be necessary. On that visit, after the warm-up you will be required to perform maximal effort against a low resistance for 2s. This effort will be repeated at 10s intervals for 4-minute trials. This test will be repeated after a 10-minute rest.

The benefits of participating in this study include the opportunity to have your maximal sprint power assessed and the force velocity characteristics of your muscles determined. The results of this pilot project will determine if this method is appropriate for future research. A of graph of your maximal power output will be given to you if you request, and an explanation of your results will be discussed with you. All data collected will remain confidential with regard to your identity. Data will be coded and any reference to your name will be destroyed upon completion of the project. To insure your safety all testing will be completed by a trained graduate student who is familiar with testing high performance athletes and the detailed safety procedures of the HPL

Your signature on this form indicates that you have understood, to your satisfaction, the information regarding your participation in this research project and agree to participate as a subject. In no way does this waive your legal rights, nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardising your relationship with the University of Calgary, or the Human Performance Laboratory in any way. The investigators reserve the right to terminate your participation in the project at any time.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification of any information throughout your participation. If you have further questions concerning matters related to his research please contact: John Holash: 220-4209 or Dr. Brian MacIntosh: 220-3431

If you have any questions concerning your rights as a possible participant in this research, please contact the office of the Vice President, Research at 220-5465, and ask for the Chairperson of the Committee of Ethics for Human Studies, at the University of Calgary.

____________________________ ____________________________

Name (Please Print) Name of Witness (please print)

________________________ __/__/__ ________________________ __/__/__

Signature Date Signature Date

Robert John Holash ________________________ __/__/__

Name of Researcher Signature Date

Appendix B

Velocity Calibrations

Velocity was calibrated in three stages

I) The range of frequencies that the velocity meter was able to convert to a corresponding voltage with the cleanest signal (high signal to noise ratio) was determined by connecting a wave generator to the velocity meter and simulating the voltage output of the light detecting diode. It was determined that the velocity meter was able to linearly convert frequencies of 27-230 Hz to a corresponding voltage.

II) The stable frequency range of the velocity meter determined in the first stage was used to determine how many bands per disk would be needed to measure pedal velocities from 30 to 160 rpm. Using the equations:

$$\text{Bands}\bullet\text{Sec}^{-1} = f_s \qquad \text{Equation 12}$$

$$f_s \bullet 60 = \text{Bands}\bullet\text{Min}^{-1} \qquad \text{Equation 13}$$

$$f_s / (Pv \bullet Gr) = bands/rev \qquad \text{Equation 14}$$

Where f_s = the signal frequency from the velocity meter box, Pv = pedal velocity in revolutions per minute, Gr = gear ratio, and where bands per revolution is the number of dark bands you require on a disk.

It was determined that a disk with 22 dark bands (gear ratio of 52:14) and a disk with 11 dark bands (gear ratio 52:7) would produce stable readings from ≈ 20 - 169 rpm of pedal rpm.

III) Actual flywheel velocity was determined by having a subject ride the cycle ergometer at six different cadences 60, 80, 90, 105, and 120 rpm, maintaining each cadence for 1 minute. The voltage output of the velocity meter was then plotted against the corresponding actual velocity (calculated from the number of pedal switch closures, 0.6 m each, per unit of time). Linear regression was used to determine an equation that was entered into the EasyLx program, for direct conversion of the sampled voltage to a velocity in $m \bullet s^{-1}$.

Unfortunately, data collected below 40 rpm and above 165 rpm was distorted by electronic noise that made these readings less accurate, particularly for estimation of acceleration. All data that were below 50 rpm and above 160 rpm were discarded. Initial test trials recorded oscillations in apparent flywheel velocity that were unrelated to actual velocity oscillations associated with cycling. These oscillations were similar to random noise reported by Seck et al. 1996, and Martin et al. 1997. The errors can be attributed to: 1) imprecise placement of the printed pattern that was bonded onto the flywheel, 2) improper alignment of the light sensing diode, 3) sample rate / disk pattern rotation harmony errors (where changes in Δ time between light and dark patterns was less than 3μs). Careful placement of the pattern disk and light sensing diode effectively reduced these errors to negligible significance but errors still existed in some of the double flywheel tests (where the greatest changes in velocity occurred). Filtering the data with a low-pass digital filter at 7Hz effectively eliminated these errors, but reduced the instantaneous recorded power by approximately 25-35%. To maintain consistency between testing protocols all velocity data were filtered using the 7Hz low-pass filter (EasyLx)

Appendix C

Raw Data From Subject 16

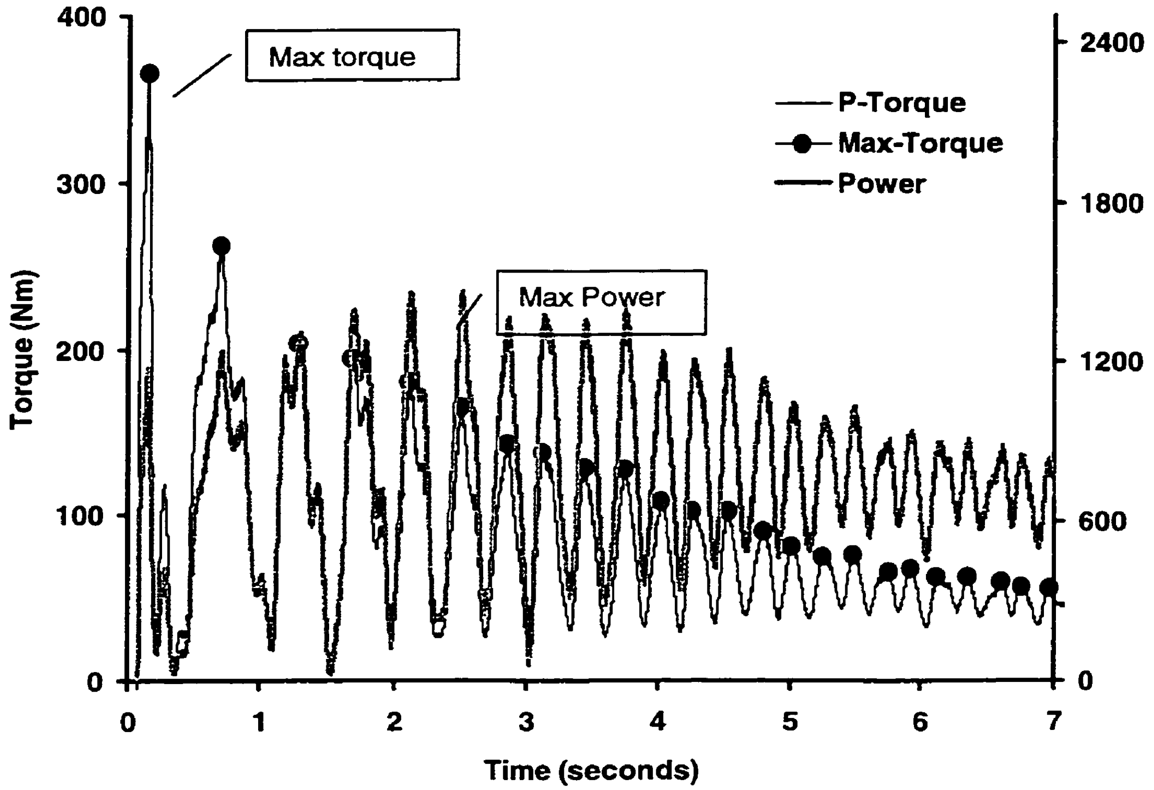

Figure 7 Power, and Torque plot from single bout test

This figure demonstrates the separation in the determination of max torque, and power, in one subject's single bout test. Maximal angular velocity was achieved at approximately 6.5 seconds (subject 16).

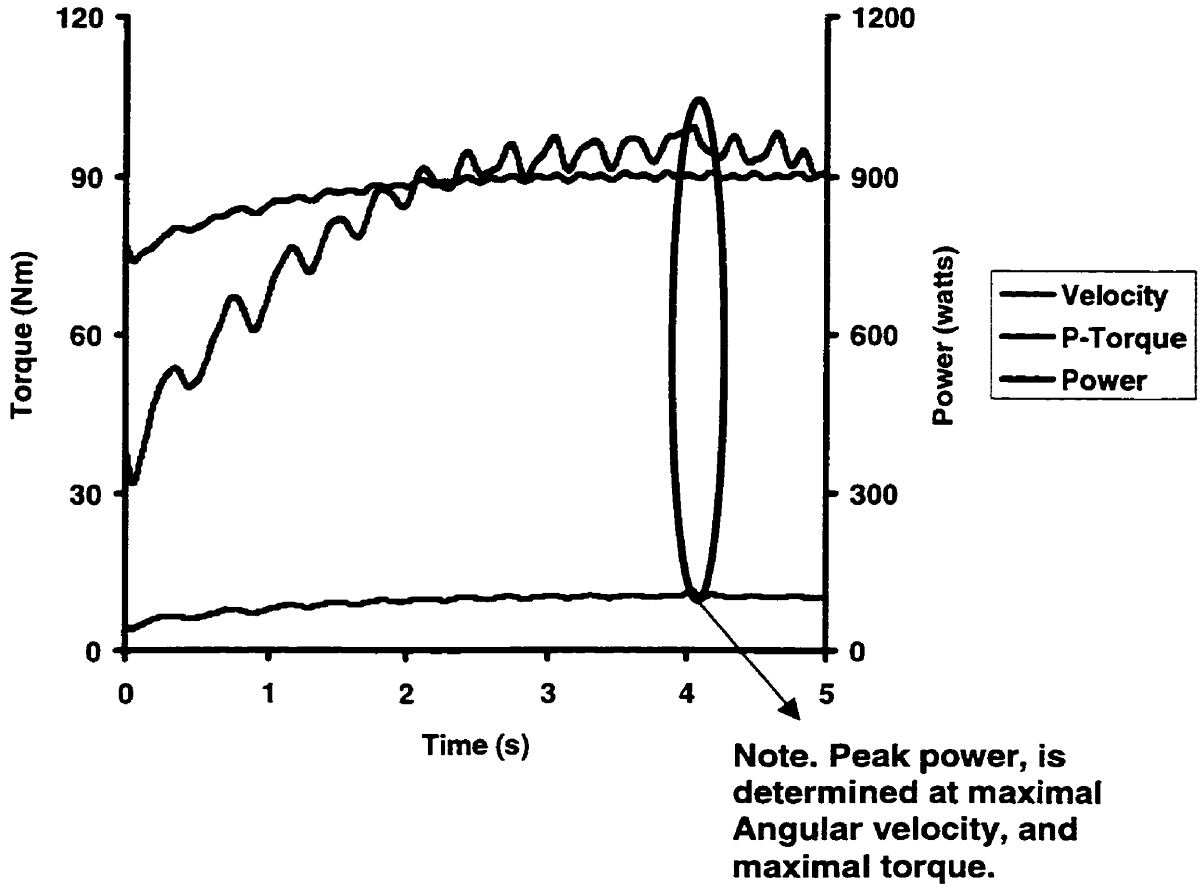

Figure 8. MT Determination of Power, Torque, & Angular Velocity

This chart demonstrates how maximal torque, and power are achieved at peak velocity in a test that does not account for inertia.

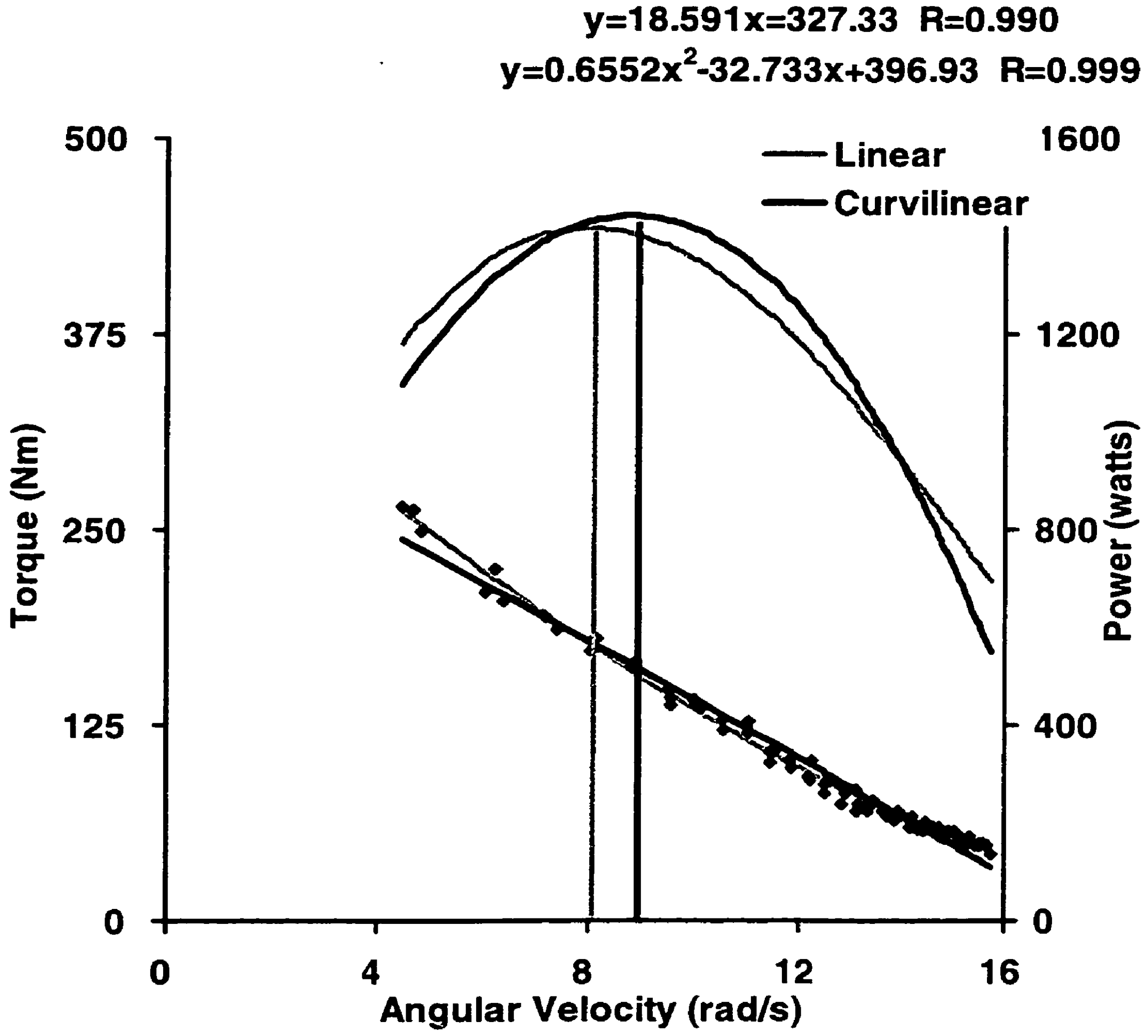

Figure 9 Linear and Exponential Fit Comparison.

This figures illustrate the difference between using a linear or, exponential fit to determine peak power (DG condition). Vertical lines cross through Peak Power, Optimal Torque, and Optimal Angular Velocity.

Appendix D

Skewness and Kurtosis of Data Sets for each Testing Condition

Table 4. Assessment of Normal Distribution.

Test Condition		Power (watts)	Angular Velocity (rad/s)	Torque (Nm)
DG	Kurtosis	-0.72	0.18	0.57
	Skewness	-0.45	1.11	-0.67
DF	Kurtosis	0.19	-0.29	-0.90
	Skewness	-0.92	0.69	-0.58
LR	Kurtosis	-0.22	-0.22	1.35
	Skewness	-0.95	0.39	-0.56
MT	Kurtosis	1.10	3.04	0.47
	Skewness	0.85	1.31	0.70
All Conditions	Kurtosis	-1.08	-0.07	-1.12
	Skewness	-0.28	0.24	-0.20

This table contains the descriptive statistics that describe how closely the distribution of data from each testing protocol resembled a “normal distribution”.

Appendix E

Inertia Calibrations

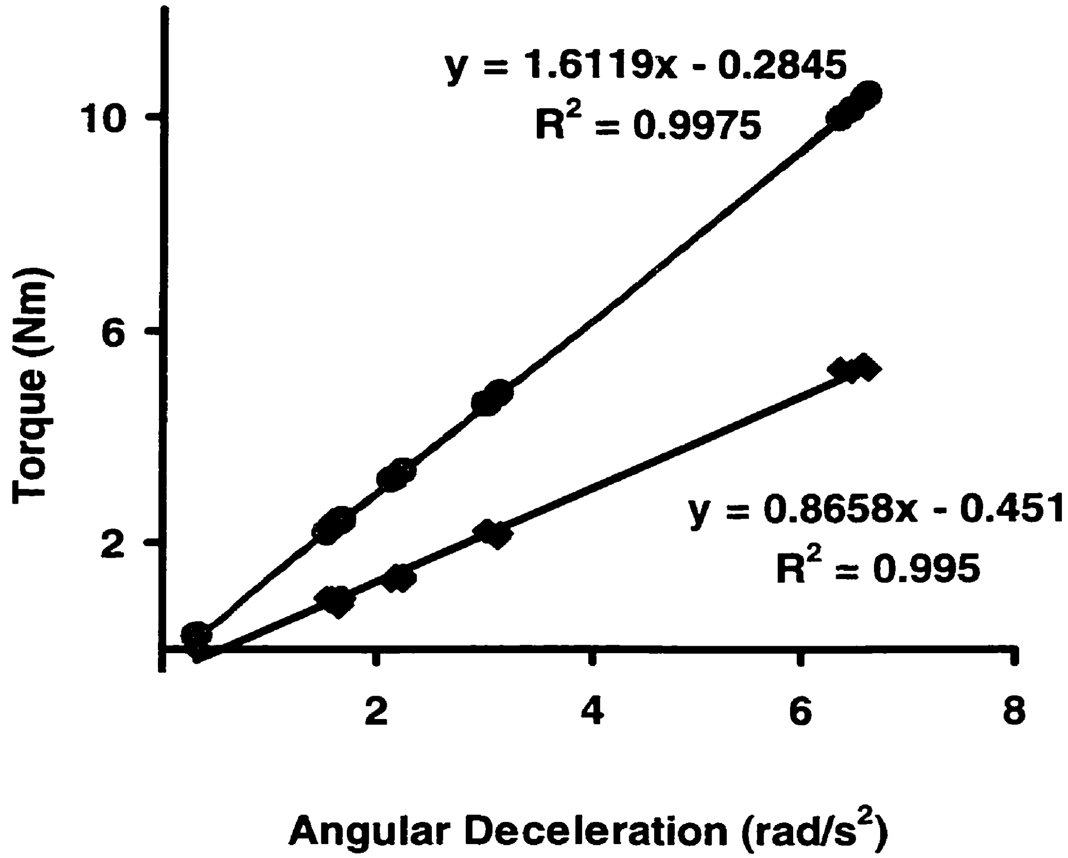

Figure 10 Moment of Inertia Spin Down Results.

There was a linear relationship for Torque vs. Angular Deceleration for both flywheel conditions: Single (lower line) and Double (upper line) flywheel. The slope of the relationship is the moment of inertia.