DEVELOPMENT AND VALIDITY ASSESSMENT OF THE MAX POWER MODEL FOR THE DETECTION, SEPARATION, AND QUANTIFICATION OF DIFFERENCES IN RESISTIVE AND PROPULSIVE FORCES IN SWIMMING

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Joshua White

DEVELOPMENT AND VALIDITY ASSESSMENT OF THE MAX POWER MODEL FOR THE DETECTION, SEPARATION, AND QUANTIFICATION OF DIFFERENCES IN RESISTIVE AND PROPULSIVE FORCES IN SWIMMING

Purpose: The purpose of this study was twofold. First, a new method, the Max Power Model (MPM), for assessing resistive (F_{res}) and propulsive (F_{prop}) forces using tethered swimming was developed. The MPM is based on the maximum power that a swimmer can deliver to an external load (P_{max}) and its relationship with the maximum velocity of the swimmer (v_{max}). The development of the MPM was accomplished in three ways: examination of the shape of the P_{max} vs. v_{max} curve, development of a method of comparing P_{max} vs. v_{max} curves, and finally testing the sensitivity of the method to large changes using the four competitive strokes and underwater dolphin kicking. Second, the validity of the MPM was assessed by comparison with the Velocity Perturbation Model (VPM) and response to independent changes in F_{res} and F_{prop} during swimming (as supplied by a pocketed dragsuit, a wetsuit, hand paddles, fist gloves).

Results: The MPM was developed effectively. The P_{max} vs. v_{max} curve was found to be best described as an exponential function. Comparisons of P_{max} vs. v_{max} curves were therefore made after linearization using the natural log of P_{max}. If the slopes were similar comparisons were accomplished using ANCOVA with v_{max} as the covariate, otherwise a t-test for differences in slope was used. The MPM was sensitive to large changes in the swimming condition as seen through significant differences ($p < 0.05$) in an ANCOVA for competitive stroke and a significantly different slope of $\ln(P_{max})$ vs. v_{max} for underwater dolphin kick in comparison with the competitive strokes. Assessment of the validity of the MPM yielded mixed results. The MPM showed a strong relationship to the VPM. However, the VPM showed no significant differences between any of the equipment treatment conditions in either the calculated F_{res} or the drag coefficient indicating. The MPM showed more promise, responding as expected to a majority of the equipment conditions.

Conclusion: While still in need of further exploration and validation, the MPM has promise as a simple method to detect, separate, and quantify differences in F_{res} and F_{prop} during swimming.

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CHAPTER 1: INTRODUCTION

Introduction

The study of swimming has long centered on the two fundamental determinants of swimming speed: the resistive forces experienced by the swimmer (F_{res}) and the propulsive forces that the swimmer can generate (F_{prop}). Knowledge of these two forces can aid swimming coaches and scientists in developing more effective stroke technique and training methods by increasing the knowledge of why swimmers are traveling at certain velocities. While much research has already been done into the factors that affect these two determinants, a single method to measure either of the two has yet to be widely accepted. Difficulties in measurement stem from three main sources. First, measurements of the force and power generated while swimming are difficult to obtain due to the inability to quantify force exerted on a fluid. Second, separating F_{res} from F_{prop} is challenging because at constant velocity they are inherently equal and opposite. The final difficulty is that F_{res} varies with velocity. Thus comparison of F_{res} must always involve consideration of the velocity at which they are measured. Four primary categories of quantifying F_{res} and F_{prop} are prevalent in the literature: extrapolation of oxygen consumption to resting values, use of the MAD System, video analysis, and swimming either with or against an external force (assisted or resisted swimming; ARS). The focus of this study is the last of these four methods. Use of ARS is more accessible due to the low cost and ease of use of the equipment. ARS is also more versatile in that it can be used with any form of swimming. Unfortunately, the methods used with ARS are currently the least developed and valid. The most well developed and widely accepted of the ARS models was introduced by Kolmogorov and Duplishcheva in 1992. This model is commonly referred to as the Velocity Perturbation Model or by the primary assumption of equal power. For the purposes of this paper, the model of Kolmogorov and Duplishcheva will be named the Velocity Perturbation Model or VPM. The goal of the study was twofold. First, a new method (the Max Power Model) for assessing resistive and propulsive forces using ARS was created and develop. The Max Power Model (MPM) is based on the maximum power that a swimmer can delivered to an external load while swimming (P_{max}) and its relationship with the maximum velocity of the swimmer (v_{max}). The MPM is an original model created by the author after study of the P_{max} vs. v_{max} relationship and study of tethered swimming. The development of the MPM was accomplished in three ways: examination of the shape of the P_{max} vs. v_{max} curve, development of a method of comparing P_{max} vs. v_{max} curves, and finally testing the sensitivity of the method to large changes using the four competitive strokes and underwater dolphin kicking. Second, the responses of the MPM and the VPM to independent changes in F_{res} and F_{prop} during swimming was examined in an effort to assess the validity of both models.

Discussion of Methods of Resistive and Propulsive Force Measurement

The study of fluid dynamics and F_{res} on rigid bodies (drag force) has identified three components of drag force: friction, form, and wave. Computational fluid dynamics can be used to predict F_{res} for a wide variety of regular rigid bodies. Unfortunately, computational fluid dynamics has not yet been able to calculate F_{res} for an non-rigid body of such an irregular shape as the human body swimming. Thus it can not be used to compute the desired values for F_{res}. This leaves the determination of F_{res} and F_{prop} for a swimming human to less direct and accurate methods such as those presented below.

The characteristics of the four current methods for determining resistive and propulsive forces will be briefly discussed. The use of extrapolation of oxygen consumption (Ext VO_2) to resting values predicts drag forces during swimming using a multistage process. VO_2 is measured while the athlete swims in a flume at a constant velocity. This process is repeated at the same velocity with the athlete being either assisted or hampered by an external force (F_{load}) supplied by a weight run over a series of pulleys and applied parallel to the direction of motion at the level of the water. The force is applied through a belt at the waist of the athlete. The VO_2 during each of these trials is plotted vs. F_{load} and a line is fit to the data. This line, representing the relationship between VO_2 and F_{load}, is extrapolated to the resting metabolic rate of the subject. The force at this VO_2 is considered to be F_{res} experienced during swimming at this velocity. The Ext VO_2 method is not only time consuming and expensive to complete, but it is also inapplicable to maximum velocity or the velocities swum during most competitive events since it cannot be used with efforts that involve anaerobic contributions. Work with the Ext VO_2 method has been completed by the following authors: di Prampero, Pendergast, Wilson, & Rennie, 1972; di Prampero, Pendergast, Wilson, & Rennie, 1974; Holmer, 1974; Pendergast, di Prampero, Craig, Wilson, & Rennie, 1977; Rennie, Pendergast, & di Prampero, 1974; Toussaint, Knops, de Groot, & Hollander, 1990; Ungerechts & Niklas, 1994; Zamparo, Capelli, Termin, Pendergast, & di Prampero, 1996.

The Measuring Active Drag (MAD) system is a series of pads placed underwater and attached to a force transducer. The swimmer pushes off of the pads instead of the water with his hands and thus F_{prop} is measured. At a constant velocity, F_{prop} is equal in magnitude to F_{res}. For the MAD method, the feet must be restrained in order to stop the swimmer from creating additional propulsion with his legs. Furthermore, the MAD method allows only for front crawl swimming. Thus this method is not easily accessible, and it is also limited in its application. Nevertheless for the range of movements that it can accommodate, the MAD system is probably the most commonly cited and readily used basis for comparison among the four methods. (Berger, Hollander, & de Groot, 1999; de Groot, Toussaint, Hollander, & van Ingen Schenau, 1990; Hollander et al., 1986; Hollander, Toussaint, de Groot, & van Ingen Schenau, 1985; Hollander, Toussaint, & Troup, 1989; Huijing, Toussaint, Mackay, vervoorn, Clarys, de Groot, & Hollander, 1988; Toussaint, 1990; Toussaint et al., 1988; Toussaint et al., 1989; Toussaint, de Groot, Savelberg, Vervoorn, Hollander, & van Ingen Schenau, 1988; Toussaint, de Looze, van Rossem, Leijdekkers, & Dignum, 1990; Toussaint et al., 1988; Toussaint, Janssen, & Kluft (1991); Toussaint, Roos, & Kolmogorov, 2004; van der Vaart, Savelberg, de Groot, Hollander, Toussaint, van Ingen Schenau, 1987).

Video analysis for determination of F_{prop} has been attempted and seen to have good agreement with other methodologies. Video analysis is a two step process. First, models of the hand and/or forearm are used to determine the drag and lift forces that they experience based on the relative velocity of the water with respect to the model. This information is then used with video of the hand and forearm of a swimmer to determine the propulsive forces of the hand and forearm during swimming. Currently video analysis has only been used with the hand and forearm, although presumably it may in the future be used with other body parts such as the feet and legs during kicking. One of the drawbacks of video analysis is that in order to truly measure propulsive and resistive forces every body part must be taken into account. Of all of the methods of determining propulsive forces, video analysis is the most environmentally valid requiring no deviation of any kind from normal swimming. Video analysis is, however, perhaps the most time consuming and most difficult to generalize of the methods. (Berger, Hollander, & de Groot, 1999; Berger, de Groot, & Hollander, 1995; Payton & Bartlett, 1995; Schleihauf, 1979; Schleihauf, Gray, & DeRose, 1983)

Unlike the other three methods of determining resistive and propulsive force, the use of swimming with or against external forces (ARS) has a number of different F_{res} calculations associated with it. Most of the models of ARS are championed only by a single author or group of authors and little testing of the validity of the models or their inherent assumptions have been completed (Clarys, 1978; Clarys, 1979; Kemper, Verschurr, Clarys, & Jiskoot, 1983; Nomura, Goya, Matsui, & Takagi, 1994; Shimonagata, Taguchi, & Miura, 2003; Shimonagata, Taguchi, Taba, Ohshiro, & Miura, 2000; Shimonagata, Taguchi, Taba, Ohshiro, & Miura, 2002; Strojnik, Bednarik, & Strumbelj, 1999; Takagi, Shimizu, & Kodan, 1999;Takagi, Shimizu, Kodan, Onogi, & Kusagawa, 1998; Takagi, Shimizu, & Nomura, 1995). The most widely accepted technique of calculating resistive and propulsive forces from swimming is the Velocity Perturbation Model (VPM). The VPM was first forwarded by Kolmogorov and Duplishcheva in 1992. The VPM involves the use of two maximal effort swims, one free swim and one swim tethered to a small F_{load}. Calculation of F_{res} is possible using the assumption that the useful propulsive power output is the same in both circumstances. The VPM has been cited, modified, and the validity has been tested by several authors

(Bideau et. al, 2003; Fomitchenko, 1999; Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997; Kugovnik, Bednarik, Strumbelj, & Kapus, 1998; Toussaint, Roos, & Kolmogorov, 2004)

The purpose of the present study was to create, develop, and evaluate a new technique (the Max Power Model; MPM) for detecting, separating, and quantifying differences in the resistive and propulsive forces during swimming. The MPM is based on the relationship between the maximum power that a swimmer can deliver to an external load (P_{max}) and the maximum free swimming velocity of the swimmer(v_{max}). The MPM was created by the author in an attempt to fill the void of an accurate and reliable method for swimming coaches to evaluate F_{res} and F_{prop} and was based on observation of the P_{max} v_{max} relationship. The MPM was developed by evaluating the relationship between P_{max} and v_{max}, determining a statistical method to quantify differences in this relationship, and testing the sensitivity of these statistical methods to large changes in the swimming condition. The validity of the MPM was evaluated by comparison to the VPM and by response to a number of modifications to the swimming condition.

The Max Power Model

Measurement of force exerted on or by a liquid during human swimming is difficult to quantify. However, portions of the force can be transferred to a source external to the liquid such as lifting a load. Hence, while total power can not be directly measured, power delivered to an external load by a swimmer can be determined by taking the product of the velocity and force of the load. The purpose of this research was to examine what can be learned from the maximum power delivered to an external load while swimming (P_{max}).

Development of the Max Power Model

The Max Power Model was developed in four ways, one theoretical and three experimental. The MPM was originally developed through an examination of the literature pertaining to tethered swimming. This literature is reviewed and used to support the face validity of the MPM in Chapter 2. In order to further develop the model, first the relationship between P_{max} and v_{max} was more closely examined than in any existing source. From this examination a method of comparing the P_{max} v_{max} curve was elucidated. Finally, the ability of the method to detect large changes was examined using the four competitive strokes and underwater dolphin kick. This was done to insure that the random error inherent in the model was not so large that it made the validity inconsequential.

While the MPM does not yield absolute values for either F_{res} or F_{prop}, it does allow for quantifiable relative values. These values can be used for comparative purposes between different styles and modes of swimming. This application is useful not only to scientists, but also to coaches. The MPM also has the potential to be able to distinguish between changes in F_{res} and F_{prop}. This virtue is in many ways more important than the ability to name absolute forces in that it allows scientists and coaches to evaluate why a swimmer is going faster or slower. With refinement, the method may be useful in comparing such concepts as changes in swimming technique, the specific properties of different forms of training, the effects of shaving the skin, and the evaluation of new swimming suits to name a few.

Validation of the Max Power Model

After the development of a new method of measurement the results are often compared to the "gold standard" or in other words a method that is documented to make the most accurate measurements. Unfortunately, for quantification of resistive and propulsive forces in swimming no true "gold standard" exists. While the results for the MPM were compared to the VPM, the validity of the VPM is itself in question. Thus the validity of the MPM was determined by the response of the method to a known stimulus. In this case, F_{res} and F_{prop} were modified independently and the changes in the measured values were compared to the expected response. F_{res} was increased by the use of a swimming suit with pockets and decreased by use of a wetsuit. These modifications were selected to minimize any changes in F_{prop}. F_{prop} was increased with the use of hand paddles which increase hand size and decreased by restriction of the size of the hand with fingerless gloves. These modifications were selected to minimize any changes in F_{res}. The response of the MPM to independent modifications in F_{res} and F_{prop} provide a basis for evaluating validity.

Research Questions and Hypotheses

The study is organized into three distinct sub-studies which are presented in manuscript form. The three studies are: determination of the shape of the relationship between P_{max} and v_{max} for front crawl and development of a method of comparing P_{max}

vs. v_{max} curves, evaluation of the relationship of P_{max} vs. v_{max} for the four competitive strokes and underwater dolphin kick (testing the sensitivity of the method to large changes), and examination of the validity of the MPM using independent modification of the resistive and propulsive forces and comparison with the VPM. The research questions and hypotheses for each of the studies are presented below.

Determination of the shape of the relationship between P_{max} and v_{max} for front crawl and development of a method of comparing P_{max} vs. v_{max} curves

Question: What function (of linear, power, and exponential) best describes the relationship between the maximum power delivered to an external load (P_{max}) and the maximum free swimming velocity (v_{max}) during front crawl swimming?

Hypothesis: A power function will best describe the relationship between P_{max} and v_{max} during front crawl swimming.

Question: What statistical method can be used to test for differences in the relationships of P_{max} vs. v_{max} between different treatments, swimming styles, and anthropometric qualities?

Hypothesis: A transformation of v_{max} based upon the power function will allow linearization of the relationship between P_{max} and v_{max}. Comparison of the P_{max} v_{max} relationship between treatments, swimming styles, and anthropometric qualities can then be accomplished using ANCOVA with the transformed v_{max} variable as the covariate.

Evaluation of the relationship of P_{max} vs. v_{max} for the four competitive strokes and underwater dolphin kick

Question: Does the relationship between P_{max} and v_{max} differ for the four competitive strokes and underwater dolphin kick?

Hypothesis: The relationship between P_{max} and v_{max} will differ for the four competitive strokes and underwater dolphin kick. Breaststroke will have the greatest ratio of P_{max} to v_{max} and underwater dolphin kick will have the smallest ratio of P_{max} to v_{max} with the other three strokes falling in between.

Examination of the validity of the Max Power Model using independent modification of the resistive and propulsive forces and comparison with the Velocity Perturbation Model

Question: Does the P_{max} vs. v_{max} relationship differ between standard front crawl swimming and 4 equipment treatment conditions during front crawl swimming: hand paddles, fist gloves, a pocketed drag suit, and a wet suit?

Hypothesis: Normal swimming and the use of hand paddles and fist gloves will all result in the same relationship between P_{max} and v_{max}, however paddles increase both the P_{max} and v_{max} of an individual and fist gloves decrease both of the variables. Normal swimming has a different relationship between P_{max} and v_{max} than does the use of a pocketed drag suit or a wet suit. When compared to normal front crawl swimming, the use of a pocketed drag suit decreases both P_{max} and v_{max} and also increases P_{max} relative to v_{max}. When compared to normal front crawl swimming, wearing a wet suit increases both P_{max} and v_{max} and also decreases P_{max} relative to v_{max}.

Question: What is the relationship between P_{max} and F_{res} obtained from the Velocity Perturbation Model?

Hypothesis: The relationship between P_{max} and F_{res} obtained from the VPM will be quadratic, but with a low level of agreement due to the large level of random error in the VPM.

Question: Can the Velocity Perturbation Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The VPM can not distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Question: Can the Max Power Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The MPM can distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Definitions

Active drag force – used in swimming literature to refer to the resistive forces experienced during swimming in which the swimmers body parts are in motion: because of the confusing nature of this term, active drag force will not be used in this paper but will be used in the Manuscripts to insure consistency with the literature

Assisted swimming – the act of swimming with a force in the direction of motion applied to the swimmer from a source other than the propulsive efforts of the swimmer

Drag force – used in swimming literature to refer to the resistive forces experienced during swimming: used in biomechanics to refer to any force that is parallel to the direction of motion: because of these differences in definition, the term drag force will not be used in this paper

Free swimming – swimming without any tethering load, usually used in discussion of tethered swimming for the purpose of distinguishing

Fully-tethered swimming – tethered swimming in which the swimmer has a velocity of 0

Kinetic resistive force (F_{kres}) – the resistive force caused by the activity of the swimmer in the water. This term comes from a model that the total resistive force (F_{res}) is the sum of the passive resistive force (F_{pres}) and an additional force (F_{kres}) cause by the activity of the swimmer

Load or Load force (F_{load}) – the load is the force against which an individual is swimming in a tethered situation

Maximum force (F_{max}) – the force produced during maximal effort fully-tethered swimming (may be the peak force or the force averaged over a period of time as the term max refers to effort)

Maximum power (P_{max}) – the largest power that can be delivered to an external force (load) during semi-tethered swimming at maximum effort regardless of the magnitude of the load

Maximum velocity (v_{max}) – the velocity of a maximum effort short duration (<45 sec) swim

Passive resistive force (F_{pres}) – the resistive force experienced by a passive swimmer

Power creating kinetic energy in the water (P_{kin}) – the power generated by the swimmer on the water which does not move the swimmer forward, but instead increases the kinetic energy of the water

Power delivered to an external load (P_{load}) – the load force multiplied by the velocity at which the load is being lifted (or sometimes by the velocity at which the swimmer is moving).

Propulsive force (F_{prop}) – the forces generated by the swimmer in the direction of motion of the swimmer

Propulsive power (P_{prop}) – the power generated by the swimmer on the water which goes towards moving the swimmer forward

Resisted swimming – this term refers to swimming against and external load or tethered swimming

Resistive force (F_{res}) – the force of the water on the swimmer in the opposite direction to the motion of the swimmer, often referred to as active drag force

Resistive power (P_{res}) – the power required to overcome the resistive force

Semi-tethered swimming (or partially tethered swimming) – tethered swimming in which the swimmer has a velocity greater than 0

Tethered swimming – the act of swimming against a force applied to the swimmer from a source other than the resistive forces of the water on the swimmer

Total power (P_{total}) – all power generated by the swimmer on the water, the sum of P_{kin} and P_{prop}

CHAPTER 2: REVIEW OF LITERATURE

Introduction

The literature relating to the determination of resistive and propulsive forces during swimming is reviewed in this chapter. The topics will be presented in three main sections: development of face validity for the Max Power Model (MPM), existing knowledge on the Velocity Perturbation Model (VPM), and methods of determining resistive and propulsive forces in swimming other than the MPM and VPM. Each topic will be further subdivided. In order to develop a convincing argument for the face validity of the MPM, the literature will be reviewed in following subtopics: (a) early history of tethered swimming, (b) fully tethered swimming, (c) semi-tethered swimming, and (d) relationships between maximum power delivered to an external load and maximum velocity or performance. The literature relating to the VPM will be dissected in the subtopics of: (a) methodology, (b) assumptions, (c) tests of validity, (d) results, (e) relationship to v_{max}, and (f) manipulations. Finally, a brief summary of the methods for determining F_{res} and F_{prop} in swimming will be given in the following order: (a) other methods using assisted and resisted swimming, (b) extrapolation of oxygen consumption, (c) the MAD system, and (d) video analysis. This informational base will allow for an informed development of the experimental design and methodology required to answer the stated research questions.

Development of face validity for the max power model

Early history of tethered swimming

As in many other fields, the history of tethered swimming is almost akin to a 'brainstorming of ideas' rather than scientific experimentation as accepted today. The studies are characterized by low subject numbers, little or no statistical analysis, and unjustified assumptions. Although inconclusive, these studies contributed a number of ideas still being explored today.

The first mention of tethering a swimmer to a weight stack was in a book entitled *The Form, Power, and Stability of Fish* published in France in 1912 (Houssay, 1912). Humans were a short deviation from the main topic, but Houssay was very insightful and his data establish a number of the premises that are currently being explored. Houssay had humans swim untethered, at various stages of partial tethering, and finally fully tethered. Thus, Houssay was the first to report measuring the maximum velocity (v_{max}) and the maximum fully tethered force (F_{max}) of the individuals tested. He also made calculations of power delivered to the external load (P_{load}), which although not being true powers as they were measured in $kg*m*s^{-1}$ were proportional to the actual power being generated. Houssay made plots of P_{load} vs. the mass of the load (proportional to F_{load}) and thus was the first to show that P_{load} had a maxima, the maximum power delivered to the external load (P_{max}), as the load increased. Houssay also published the raw data that he obtained and thus some simple analyses can be completed. Houssay's data show a linear relationship between velocity and load. In fact of the 12 trials of 5 subjects in 3 different strokes, the lowest linear correlation between velocity and load is 0.94 with an average linear correlation of 0.97. In 1912, the modern swimming strokes had not yet been developed and thus the strokes used by Houssay were breaststroke, over arm side stroke, and breaststroke on the back (or elementary backstroke). The data of Houssay shows a relationship between P_{max} and v_{max}. Ignoring differences in stroke due to the low subject numbers, the linear correlation between v_{max} and P_{max} is 0.91. The purpose of Houssay's research with humans was to compare the F_{max} of humans and fish relative to body mass. He noted that the fish he was studying were able to reach F_{max} values of approximately double body weight, while the humans were only able to reach F_{max} values of approximately 1/10th body weight.

The next published study focused on human propulsion that utilized tethered swimming was by Karpovich and Pestrecov in 1939. Karpovich and Pestrecov determined passive drag coefficients for two individuals by pulling them through the water using a weight stack. After the weight had reached the bottom and was no longer exerting a force on the swimmer, the decay of velocity during this gliding phase was examined for determination of a passive drag coefficient ($k_{passive}$). Karpovich and Pestrecov do not acknowledge that the passive and active drag coefficients may be different and thus they use the formula $F = k_{passive}v^2$ to determine the propulsive force required at any given velocity during swimming. Using the maximum front crawl velocity of the three subjects that they tested, the authors predicted the propulsive force that would be required to reach this velocity. Each swimmer then swam front crawl against this force on the weight an pulley stack and it was found that each swimmer could in fact move forward slowly at this weight. Karpovich and Pestrecov went on to measure the F_{max} of the three subjects and gave comparisons of the calculated maximum propulsive force and F_{max} (converted to N from kg).

Table 1

Subject	Predicted F_{prop} (N)	F_{max} (N)
R	95.94	112.52
H	103.01	123.51
L	121.74	136.26

TABLE 1 - Propulsive Force (F_{prop}) predicted using $k_{passive}*v^2$ in comparison to the fully tethered force (F_{max}) of swimmers from Karpovich & Pestrekov (1939)

The authors noted that the calculated propulsive force was always lower than F_{max}. This occurs for three reasons, two of which the authors did not take into account. First, they used $k_{passive}$ which is likely to be smaller than k_{active} in their calculations thus deflating their calculated F_{prop} values. Second, as the authors note the power of velocity is likely slightly larger than 2, and the use of velocity squared once again deflates the calculated F_{prop} values. Finally, and perhaps most importantly in terms of future research, F_{max} is determined in water which is not moving and thus the ability to create propulsive force is larger than in water moving at the maximum velocity of the subject. While Karpovich and Pestrecov may have made a couple of errors in calculation, they do grasp the fundamental concepts of the study and allude to the future of these types of measures when stating, “For the same speed, water resistance in the breast stroke is much greater than in the smooth gliding crawl stroke; therefore, at the same speed the amount of work done in the breast stroke is greater.”

The first mention of assisted swimming in the literature is seen in a 1953 article by Alley entitled “An analysis of water resistance and propulsion in swimming the crawl stroke”. Alley used a single male subject who was an All-American at the State University of Iowa and all of the trials were done with the front crawl stroke. The experimental apparatus was actually quite complex and involved a motor on a platform which was hung as a pendulum a short distance from the wall of the pool. The motor was used to both assist the swimmer and resist the swimmer at a variety of different forces. The force was measured by a transducer which was connected to the pendulum and to the side of the pool. While the use of a single subject makes the results unable to be generalized, Alley did introduce a number of new concepts to this area of study. Alley was attempting to examine differences in stroke technique using ARS techniques. Alley was the first to identify the linear relationship between tethering force and velocity. As previously mentioned he was also the first to measure forces and velocities during assisted swimming. Alley also made separate measurements for kicking, pulling, and swimming and more importantly he had the subject swim with different variations of the stroke which included normal and small amplitude kicking and normal and “bent arm” stroking. Furthermore, the stroke frequency of the individuals was held constant in order to regulate effort. These concepts are integrally linked to future study.

In 1955 also at The State University of Iowa, Counsilman used an apparatus very similar to Alley’s in order to examine the resistive and propulsive forces of different forms of front crawl swimming. Three All-American swimmers completed semi-tethered swimming at 10 different velocities using two different derivations of front crawl, one in which the arm stroke was continuous and one in which the subject was encouraged to glide at the end of each arm stroke. Each of these front crawl derivations was examined at two different stroke frequencies which were determined based upon the average frequencies used in the 100 m free and the 1500 m free at the most recent AAU nationals. Due to the large number of variables and the small number of subjects the results were inconclusive.

This brief historical perspective introduces the majority of the measurements whose interpretations are still being examined. While the data collection has become at the same time more sophisticated and simplified, it is based upon the ideas introduced by 1955.

Fully tethered swimming

Introduction

During tethered swimming, propulsive force can be made useful to one of two ends: exerting force on the tether or propelling the body forward in the water. The most simplistic model of propulsive force determination is to fully tether an individual at which point all of the propulsive force is exerted against the tether. At maximum effort, this force is termed F_{max}. Unfortunately, the assumption that F_{max} is equal to the propulsive force during maximal free swimming is incorrect. The force that can be exerted against the water depends not only upon the motion of the body, but also the motion of the water beneath the body. The ability to generate force on stationary water, the condition during fully tethered swimming, is greater than the ability to generate force on water moving in the opposite direction of the body. This situation is similar to pushing off the street with one's foot on a moving skateboard which generates less force than on a stationary skateboard. While the difficulty of water movement erases the possibility of a direct measurement of propulsive force, F_{max} is still a good qualitative estimation of the propulsive force and the large volume of literature on the topic can shed some light on a number of methodological considerations which will aid in future study.

There are several important differences, beyond merely subject swimming ability, in measurements of F_{max} to keep in mind when examining the literature. First, the measurements can be made using a non-elastic tether or an elastic tether. A non-elastic tether is usually merely a metal cable. The primary characteristic of a non-elastic tether is that it will immediately record a force of 0 when no force is being applied to the tether. In this way the intra-cycle variations in the swimming stroke are seen as large ranges in force production during a single stroke cycle. On the other hand, an elastic tether will gradually return to a recorded force of 0 when no force is applied. The elasticity of the tether will continue to apply a force to the measuring device throughout all phases of the stroke cycle thus dampening the intra-cycle variations in force. Second, the duration of the swim must be taken into account when examining fully tethered swimming. As the forces are almost always recorded at maximum effort, the duration of the swim will effect the force produced as will the instructions regarding the pacing of the effort. Third, while most of the studies involve only front crawl, some may involve other strokes. Differences among the strokes is of interest in the proposed study in which the four competitive strokes and dolphin kick are examined.

In order to discuss the literature with clarity, the information pertaining to front crawl will be discussed first beginning with values of F_{max} from elastic tethers and then non-elastic tethers. Next, the relationships between F_{max} and v_{max} or performance for front crawl will be explored. Finally, information regarding strokes other than front crawl will be surveyed.

Front crawl values for F_{max}

Elastic tethers

Studies that use elastic tethers are more rare than those with non-elastic tethers. There are five studies that use elastic tethers (Bednarik, Kugonic, Kapus, & Strojnik, 1992; Keskinen, Tilli, and Komi, 1989; Rohrs, Mayhew, Arabas, & Shelton, 1990; Rohrs & Stager, 199; White, Stager, Tanner, Simmons, & Naganobori, 2003). Two do not report any values for F_{max} and are thus not useful for this discussion (Bednarik, Kugonic, Kapus, & Strojnik, 1992; White, Stager, Tanner, Simmons, & Naganobori, 2003). The earliest reference to an elastic max force measurement was made by Keskinen, Tilli, and Komi in 1989. A bungee cord was attached to a force transducer on one end and the waist of a swimmer on the other end. The subject population was a group of young male competitive swimmers (N = 33, age = 17.89 ± 3.69 years, mass = 66.9 ± 13.2 kg, height = 176.9 ± 10.2 cm) with an average best competition 100 m freestyle time of 59.56 ± 4.97 s (the length of the pool was unreported) for an average velocity of 1.68 m/s. Among this population the average value for F_{max} = 144.4 ± 34.5 N. The authors report that the maximum force was found within the first 5-10 seconds of the test and imply that the test was only as long as necessary to find this peak. While this study was centered towards an exploration of propulsive force, the other two studies were geared more towards measurements of anaerobic power (Rohrs, Mayhew, Arabas, & Shelton, 1990; Rohrs & Stager, 1991). The reported maximum tethered forces in these articles are found as a part of the ‘Swimgate Test’. The Swimgate is a modification of the Wingate cycling test for use during swimming. The Swimgate is a 30 second maximal effort swim with no pacing. Similar to Keskinen, Tilli, and Komi, the setup involves an elastic cord attached to the waist of the swimmer and a force transducer, and the maximum values for force were normally recorded within the first 5-10 seconds of the test. In the earlier of the two studies using the Swimgate (Rohrs, Mayhew, Arabas, & Shelton, 1990), the F_{max} values are reported relative to body mass making them more difficult to interpret in relation to other values. The final article by Rohrs and Stager (1991) reports force values in kg which are not units of force, but can be converted into N for comparison purposes. For a population of competitive male age-group swimmers (N = 39, age = 15.9 ± 1 years, mass = 64.4 ± 7 kg, height = 174.9 ± 6.1 cm) with an average velocity over 100 yards of 1.68 ± 0.09 m/s, the average F_{max} = 122.5 ± 16.7 N. These values compare quite closely with those of Keskinen, Tilli, and Komi not only on descriptive variables, but also on the ability level of the swimmers and the F_{max} obtained. The similarity of the values probably results from the close similarity of methodology used despite differing purposes.

Non-elastic tethers

Before examining the correlational relationships seen in these studies, the values for F_{max} from the studies using non-elastic tethers will be surveyed. Unlike the studies using elastic tethers, this group of studies has a rather wide variation in testing protocol. In order to accommodate this difference, the studies will be discussed in order of duration of swimming during the test beginning with the shortest duration (3 sec) and ending with the longest duration (3 min). Christensen and Smith (1987) examined 39 competitive swimmers (24 male, 15 female) ranging in age from 14-20 years old. The protocol involved a 2 second buildup period and then a 3 second maximal effort swim. This swim was completed twice with a period of rest in between and the larger values for force were recorded and used for comparison The values reported for F_{max} were the peaks of force and were reported in lbs, which are converted to N for the purposes of comparison. For males $F_{max} = 353.6 \pm 56.2$ N and for females $F_{max} = 244.8 \pm 35.7$ N. The maximum velocity for each individual was also measured by taking the average velocity over a 25 yard sprint timed from the foot leaving the wall to the first hand touching the opposite wall. For males $v_{max} = 2.00 \pm 0.08$ m/s and for females $v_{max} = 1.79 \pm 0.07$ m/s. In order to compare these values to those obtained using elastic tethers, the study by Rohrs and Stager (1991) contained, in addition to average velocity over 100yd, average velocity over 25yd. For a 25 yard swim, the subjects in the study by Rohrs and Stager had an average $v_{max} = 1.78 \pm 0.09$ m/s. This velocity is comparable to the females in the study by Christensen and Smith, however the females reach an F_{max} of approximately double that found by Rohrs and Stager. This is likely due to the dampening effect of the elastic tether. This dampening effect makes the F_{max} value obtained during elastic tethered swimming similar to the average force using non-elastic tethered swimming as opposed to the peak force as was used for F_{max} by Christensen and Smith. Unfortunately for purposes of comparison, Christensen and Smith do not report the average force over the three second period.

In a similar range of test duration, Yeater, Martin, White and Gibson (1981) reported values for F_{max} determined over three front crawl stroke cycles (~2.5-5 seconds) with a non-elastic tether. These authors reported both the average F_{max} over that time period and the peak of F_{max}. The subjects were 18 males from the 1978-79 West Virginia University Swimming team. The average best competition velocity for the 100 yard front crawl was 1.85 ± 0.08 m/s. The average F_{max} = 191 ± 41 N while the peak F_{max} = 384 ± 77 N. As these swimmers are greater in ability than any of those previously discussed, it is expected that the F_{max} values for them should be somewhat larger. This is verified when the peak F_{max} values are compared to those of Christensen and Smith (1987) which are comparable but somewhat lower. Also the average F_{max} values are comparable to the values obtained in the elastic tether studies lending credence the to idea that the dampening effect of the elastic tether makes the peak F_{max} of an elastic tether similar to the average F_{max} of a non-elastic tether.

Moving up in test duration slightly are three studies with test durations between six and ten seconds. Ria, Falgairette, and Robert (1990) measured the average F_{max} over a six second period in a group of "unspecialized" prepubertal boys (N = 20, age = 11.5 ± 0.12 years, mass = 38.4 ± 7.8 kg, height = 147.6 ± 9.7 cm) who trained at swimming for 4 hours per week. The boys had an average competition best 100 m velocity of 1.21 ± 0.19 m/s and an average free swimming velocity during a 6 second maximal effort of v_{max} = 1.29 ± 0.13 m/s. The average F_{max} over 6 seconds was 54.6 ± 16.4 N. These lower than previously seen values for F_{max} are not unexpected as they correspond to the weaker swimming ability of the subjects as exemplified by the lower values of v_{max}.

Sidney, Pelayo, and Robert (1996) reported the peak F_{max} during a 7 second maximal effort non-elastic tethered test for two groups of males swimmers. The groups were divided based upon swimming ability and were categorized as either national level (N = 21, age = 18 ± 1.5 years, mass = 69.39 ± 4.83 kg, height = 177.9 ± 4.7 cm) or average front crawl swimmers (N = 17, age = 12 ± 0.5 years, mass = 43.12 ± 9.14 kg, height = 154.5 ± 11.3 cm). In addition to the difference in ability level and the readily apparent differences in age and training (13 ± 1.5 hrs/wk vs. 4 ± 1 hrs/wk for national level and average swimmers respectively), there were significant differences ($p < 0.01$) in height and mass as determined by a series of t-tests. There were also significant differences between the two groups in F_{max} (371.9 ± 78.1 N vs. 207.8 ± 52 N for national level and average swimmers respectively) and competition 50 m front crawl velocity (1.92 ± 0.08 m/s vs. 1.36 ± 0.11 m/s for national level and average swimmers respectively) as determined by t-test ($p < 0.01$). The competition 50 m front crawl velocity used was the best of the subject within one month pre or post data collection. These values for peak F_{max} are in the same range as those reported by Christensen and Smith (1987).

The last study in this category of test duration was reported in abstract form by Mookerjee and Pendergast (1992). The limited nature of an abstract makes interpretation of the methodology challenging, but it appears that the average F_{max} over 10 seconds was found in groups of males and females separated by age into groups of 8-13 year olds and 14-17 year olds. A total of 12 males and 13 females were tested, but the number of subjects falling into each group is not reported nor are any descriptive anthropometries. The abstract makes mention of the collection of values for v_{max}, but they are not reported. The reported values of F_{max}, converted from kg to N, for front crawl are reported in table 2. These values are in the range of the younger swimmers in the study by Ria, Falgairette, and Robert. Comparison of ability level is not possible due to lack of information. At a maximal effort of 10 seconds, F_{max} may be decreased due to a change in energy system from immediate sources (ATP-CP) to short term sources (Glycolytic).

The next group of studies will indubitably have different values of F_{max} due to longer durations of the test and the utilization of different energy systems.

Table 2

Age	Sex	F_{max} (N) Mean	F_{max} (N) SD
8-13	M	43.46	7.26
8-13	F	47.68	14.81
14-17	M	54.54	25.9
14-17	F	55.23	14.81

TABLE 2 - Average force over 10 s at maximal effort using a non-elastic tether separated by gender and age range from Mookerjee & Pendergast (1992)

Two studies have examined F_{max} using non-elastic tethers at greater test durations than 10 s. Mosterd and Jongbloed (1964) tested 10 female and 5 male front crawl swimmers training for the Olympic games to determine average F_{max} over a maximal effort of both 20 seconds and 60 seconds. While descriptive anthropometries are not presented, the data for each subject is presented with units of kg for F_{max} and the average competition velocity for the 100 m front crawl. From this information, averages for men and women were computed and are presented in Table 3. In order to test for a change in F_{max} with duration, a paired t-test was possible due to the presentation of the raw data. Due to the low subject numbers, the sexes were pooled into a single group. There was a significant difference between the F_{max} over 20s and those over 60s ($p<0.01$). Thus as expected, the 60 second trial showed a lower F_{max} not only on average but also in each case. These values also appear to be a decrease from subjects of like ability over shorter duration seen in previous studies. A comparative table for all of the studies is presented as Table 4.

Table 3

Sex	F_{max} 20s (N)	F_{max} 60s (N)	100m vel (ms^{-1})
Female	86.3 ± 14.2	72.2 ± 10.9	1.53 ± 0.04
Male	131.8 ± 9.4	101.2 ± 3.6	1.71 ± 0.02

TABLE 3 - Average force on a non-elastic tether over 20 and 60 s at maximal effort along with average velocity during a 100 m maximal effort free swim from Mosterd & Jongloed (1964)

The last remaining study presenting values for F_{max} is that of Magel (1970). Magel determined the average F_{max} for the last 120 seconds of a 180 second effort for highly trained male swimmers from the University of Michigan (N =11, age = 20 years, mass = 76.3 kg, height = 181.3 cm). The best competition average velocity for the 100yd front crawl for these subjects was 1.84 m/s. The mean F_{max} value for the group was 76.4 N. A decrease in average F_{max} is seen in comparison with the study of Mosterd and Jongloed (1964). Thus it seems that in spite of the greater ability level of the subject of Magel, the increase in duration of the test causes a decrease in the average F_{max} value.

To summarize the literature on the values of F_{max} for front crawl, the peak F_{max} values of the elastic tether appears to be comparable to the average F_{max} values of the non-elastic tether due to the dampening effect of the elastic tether. F_{max} values increase as the swimming ability of the subject increases. Finally, average F_{max} values decrease as the duration of the test increases as would be expected based upon knowledge of energy systems. Table 4 groups all of the previously discussed studies in a logical format.

Table 4

Lead Author	Year	Tether	Sex	F_{max} Test Duration(s)	Average F_{max} (N)			Peak F_{max} (N)			v_{max} (ms^{-1})			Comp 100yd/m v(ms^{-1})		
Keskinen	1989	Elastic	M	5-10				144.4	±	34.5				1.68		
Rohrs	1991	Elastic	M	5-10				122.5	±	16.7	1.78	±	0.09	1.68	±	0.09
Christensen	1987	Non-Ela	M	3				353.6			2.00	±	0.08			
Christensen	1987	Non-Ela	F	3				244.8			1.79	±	0.07			
Magel	1970	Non-Ela	M	180	76.4									1.84		
Mookerjee (old)	1992	Non-Ela	M	10	54.5	±	25.9									
Mookerjee (old)	1992	Non-Ela	F	10	55.2	±	14.8									
Mookerjee (young)	1992	Non-Ela	M	10	43.4	±	7.3									
Mookerjee (young)	1992	Non-Ela	F	10	47.7	±	14.8									
Mosterd	1964	Non-Ela	M	20	131.8	±	9.4							1.71	±	0.02
Mosterd	1964	Non-Ela	F	20	86.3	±	14.2							1.53	±	0.04
Mosterd	1964	Non-Ela	M	60	101.2	±	3.6							1.71	±	0.02
Mosterd	1964	Non-Ela	F	60	72.2									1.53	±	0.04
Ria	1990	Non-Ela	M	6	54.6	±	16.4				1.29	±	0.13	1.21	±	0.19
Sidney	1996	Non-Ela	M	7				371.9	±	78.1	1.92	±	0.08			
Sidney	1996	Non-Ela	M	7				207.8	±	52	1.36	±	0.11			
Yeater	1981	Non-Ela	M	2.5-5	191	±	41	384	±	77				1.85	±	0.08

TABLE 4 - Data on fully tethered force at maximal effort (F_{max}) from all sources

The relationship of F_{max} to v_{max} and performance

Perhaps more important than the absolute values of F_{max} is the relationship of F_{max} to either the maximum velocity of free swimming (v_{max}) or in lieu of this, a performance measure such as a best competition time. Because the focus of the proposed study is relationships involving v_{max}, only competitive performances of 100 m or less shall be considered in this discussion. The relationship between F_{max} and v_{max} is seen in three primary ways: statistical comparison of groups of disparate abilities, linear correlations between F_{max} and v_{max} or performance, and non-linear correlations between F_{max} and v_{max} or performance.

There are two articles which examine the relationships involving F_{max} by comparing the F_{max} of two groups with differing abilities. The work of Sidney, Pelayo, and Robert (1996) has already been mentioned as reporting significant differences in F_{max} between groups of widely different characteristics. In this case, the groups are different in such a wide variety of ways, for example maturity and lean body mass, that the differences in F_{max} seen between the groups can not be directly attributed to the differences in v_{max}. Similarly Adams, Martin, Yeater, and Gilson (1983) compare the F_{max} of males and females from a non-elastic tether as well as the v_{max} values for the respective groups of collegiate swimmers ($N = 9$ and $N = 9$ respectively). The duration of the effort was 10 seconds, but information on whether the peak or average F_{max} was used for comparisons is absent from the article. The results showed that females had 16% lower F_{max} and 1.5% lower v_{max}. This may be indicative of a relationship, but sex difference clouds the issue. In fact, when normalized for body mass there were no differences in F_{max} between the males and females. When normalized for lean body mass the females showed a 7% greater relative value of F_{max} than the males. While informative, these results are published in a non-peer reviewed journal and thus lack some credibility and some of the specific information and rigor on statistics and anthropometrics expected. The article does, however, provide a nice segue into the next organizational grouping. The article mentions that no significant linear correlations were found between F_{max} and v_{max} or 100 yard competition best time, except when analyzing males alone in which a significant linear correlation of $R = 0.465$ is seen between F_{max} and v_{max}.

Presented in Table 5 are the linear correlations found in the papers discussed in the previous section as well as those from two new sources. Fomitchenko (1999) tested F_{max} using a non-elastic tether for a seven second maximal test and found the simple regression to average velocity over a maximum effort 25m swim in a population of 56 male swimmers. The swimmers were divided into three groups by age (averages 11.5, 13.8, and 17.4 years) and descriptive statistics of v_{max} were reported (1.36 ± 0.04, 1.46 ± 0.13, and 1.76 ± 0.03 m/s respectively). Jensen and Tihanyi (1978) present data using ten female (age 9-15) and five male (age 11-15) competitive age group swimmers. F_{max} was found using a non-elastic tether for a duration of 30 seconds of paced maximal effort of which the last 10 seconds were recorded and analyzed. Ability of the subjects was quantified using best competition average velocity in the 100, 200, and 400 m front crawl events. In addition to the new sources, it is important to note that the population used for correlational research by Yeater, Martin, White, and Gilson (1981) is a subpopulation of 5 athletes categorized as sprinters and the correlations from Mosterd and Jongbloed (1964) were calculated from the raw data presented in the article.

Table 5

Lead Author	Tether	Sex	F_{max} Test Duration(s)	Avg/Peak	v distance	R
Rohrs (1991)	Elastic	M	5-10	Peak	25	0.53
Rohrs (1991)	Elastic	M	5-10	Peak	50	0.63
Rohrs (1991)	Elastic	M	5-10	Peak	100	0.55
Christensen	Non-Ela	F	3	Peak	25	0.576
Christensen	Non-Ela	M	3	Peak	25	0.685
Yeater	Non-Ela	M	2.5-5	Avg	100	-0.086
Fomitchenko (11y)	Non-Ela	M	7	Avg	25	0.733
Fomitchenko (13y)	Non-Ela	M	7	Avg	25	0.752
Fomitchenko (17y)	Non-Ela	M	7	Avg	25	0.413
Mosterd	Non-Ela	Mix	20	Avg	100	0.85
Jensen	Non-Ela	F	30	Avg	100	0.49
Jensen	Non-Ela	M	30	Avg	100	0.98
Mosterd	Non-Ela	Mix	60	Avg	100	0.81

TABLE 5 - Linear correlations of F_{max} with max effort free swimming velocity indicating the type of tether (elastic or non-elastic), whether the force used was a peak or average, and the distance over which the velocity was measured

In contrast to the values of F_{max}, interpretation of the differences in correlation coefficients between studies is difficult even when the duration of the test and the ability of the subjects is taken into account. The largest difficulty is the assessing the variability of the subject population. In the case of F_{max} it is quite logical to expect that a population with a large variation in v_{max} or sprint swim performance will have a larger correlation coefficient than a population with small variation. Therefore, it is informative to look at the standard deviation of the velocities. The standard deviation of the velocities of all studies lie between 0.03 and 0.13 m/s. However, no pattern between velocity variability and correlation between F_{max} and v_{max} is prevalent. Evaluation of variability in F_{max} based upon the variability of v_{max} requires the assumption that the relationship between F_{max} and v_{max} is linear. If the relationship between F_{max} and v_{max} is not linear, then variability in the independent variable (v_{max}) may not be indicative of variability in the dependent variable (F_{max}). In the case of a non-linear relationship between F_{max} and v_{max}, the correlative strength may depend not only on the variability in the v_{max} measure but also on the absolute value of v_{max}. However inclusion of the absolute value of v_{max} does not help to further explain the different strengths of correlations between F_{max} and v_{max} seen in the literature, nor do differences in the duration of the F_{max} test, the duration of the v_{max} measure, or the tether type. Indeed, no patterns emerge and the similarities in the absolute values for F_{max} seem to rule out inherent differences in methodologies. Likely, the differences in correlations are due to differences in the random error seen in each methodology. Perhaps the best conclusion that can be drawn from the literature is that there is indeed a linear correlation between F_{max} and v_{max}, but the strength of the relationship is still somewhat in question.

As alluded to in the previous paragraph, information regarding the relationship between F_{max} and v_{max} or performance can also be gained from going beyond the first order linear correlation to look at the shape of the relationship. Keskinen, Tilli, and Komi (1989) graphed the relationship between F_{max} and v_{max} and fit the best second order polynomial, $F_{max} = -90 + 97.256*v_{max} - 21.301*v_{max}^2$ ($R = 0.86$). While this polynomial may have produced a slightly larger correlation and thus serve as a better predictor than a linear fit for this specific data, the function is theoretically illogical. The theoretical function must run through the origin as a v_{max} of 0 should correspond to an F_{max} of 0. White, Stager, Tanner, Simmons, and Naganobori (2003) measured F_{max} using the same methodology as Rohrs and Stager (1991). The authors determined v_{max} using the middle 15yd (13.72 m) of a 25yd (22.86 m) maximal effort swim in a group of male and female competitive swimmers ($N = 156$, age = 17.0 ± 2.3 years, mass = 65.7 ± 10.3 kg, height = 172 ± 8 cm). These authors evaluate the relationship between F_{max} and v_{max} as being curvilinear and best described by either a power function $F_{max} = 46.664*v_{max}^{1.8168}$ ($R = 0.84$) or an exponential function $F_{max} = 14.949e^{1.2376v_{max}}$ ($R = 0.85$).

In contrast to the regular and explainable values for F_{max} in the literature, the relationship of F_{max} to v_{max} and performance is less of a consensus. While it is apparent that a relationship does exist, the nature and strength of this relationship remain unconcluded.

Strokes other than front crawl

As in most areas of swimming research, information on strokes other than front crawl is much less plentiful, but does exist. For the purposes of the proposed study, the relationships between the F_{res} and F_{prop} of the competitive strokes is of great interest. Discussion of the other competitive strokes will follow an abbreviated version of the outline for freestyle. Values for F_{max} will begin the discourse followed by the relationships of F_{max} to v_{max} or performance and concluding with a comparison of the strokes.

As can be seen in Table 6, information regarding butterfly, backstroke, and breaststroke is indeed sparse. All of the studies referenced in the table have been previously cited and share certain characteristics. They all are studies done using non-elastic tethers and reporting average F_{max}. The subjects are in most cases a subsample of the population of the study and descriptive anthropometrics or performance criteria are not presented. The relation of F_{max} values between the studies seems to hold from front crawl to each of the other strokes. If the assumption that swimming ability, at least to a certain extent, transcends stroke, then it can be tentatively said that strokes other than front crawl follow similar trends of F_{max}. F_{max} tends to be larger for faster swimmers and also for shorter measurement durations.

Table 6

Lead Author	N	Sex	Fmax Test Duration(s)	Average Fmax (N)	Comp 100yd/m v(m/s)	R
Butterfly						
Mookerjee (young)		M	10	45.22 (25.11)		
Mookerjee (young)		F	10	29.72 (4.41)		
Mookerjee (old)		M	10	53.27 (5.00)		
Mookerjee (old)		F	10	27.76 (5.59)		
Mosterd	1	M	20	128.5	1.58	0.99
Mosterd	3	F	20	63.1 (2.5)	1.42 (0.00)	
Mosterd	1	M	60	97.1	1.58	0.96
Mosterd	3	F	60	55.3 (4.4)	1.42 (0.00)	
Magel	4	M	180	78.4		
Backstroke						
Yeater	17	M	2.5-5	156 (43)		
Mookerjee (young)		M	10	33.35 (19.33)		
Mookerjee (young)		F	10	28.06 (11.09)		
Mookerjee (old)		M	10	41.79 (5.79)		
Mookerjee (old)		F	10	28.15 (5.79)		
Mosterd	2	M	20	136.8 (21.5)	1.52 (0.02)	0.76
Mosterd	4	F	20	110.2 (11.5)	1.42 (0.05)	
Jensen	5	M	30			0.92
Jensen	10	F	30			0.35
Mosterd	2	M	60	105.9 (18.0)	1.52 (0.02)	0.76
Mosterd	4	F	60	89.3 (7.7)	1.42 (0.05)	
Magel	4	M	180	84.28		
Breaststroke						
Yeater	15	M	2.5-5	188 (51)		
Mookerjee (young)		M	10	67.98 (24.23)		
Mookerjee (young)		F	10	62.10 (21.19)		
Mookerjee (old)		M	10	86.33 (10.01)		
Mookerjee (old)		F	10	65.73 (15.30)		
Mosterd	3	M	20	196.2 (24.1)	1.26 (0.07)	0.74
Mosterd	2	F	20	141.8 (14.6)	1.22 (0.00)	
Mosterd	3	M	60	151.1 (16.7)	1.26 (0.07)	0.78
Mosterd	2	F	60	110.4 (16.0)	1.22 (0.00)	
Magel	6	M	180	89.2		

TABLE 6 - Values of F_{max} found in the literature for strokes other than front crawl along with the average velocity over 100yd or 100 m in competition and the linear correlations between the two

Information on the relationship between F_{max} and the competition best 100 yd/m average velocity is primarily limited to calculations that can be made from the data of Mosterd and Jongbloed (1964). These computations involve very few subjects and thus despite the high correlative values must be considered suspect. As with front crawl, the only conclusion that can be drawn from this data is that a relationship of some variety likely exists.

Comparison of the four competitive strokes shows a trend towards larger values of F_{max} for breaststroke than the other three strokes with other comparisons varied by authors. Presentation of the raw data allows for statistical analysis of the study of Mosterd and Jongbloed (1964). When a 2-way ANOVA for sex and stroke is run for each of the 20 and 60 second trials, the results of both analyses are similar. While no significant interaction is found, both main effects are significant. Further analysis with a Bonferroni adjustment shows that males have significantly higher F_{max} values than females ($p < 0.05$) and that breaststroke has a significantly higher F_{max} than all of the other strokes with no other stroke to stroke differences observed.

Since a relationship between velocity and F_{max} has already been established, the analysis is furthered with an ANCOVA for sex and stroke with a covariate of competition best 100m average velocity. The analysis for both the 20s and 60s duration F_{max} tests once again yield the same results. The means and standard errors for the covariance (which tests at 1.49 m/s) are shown in Table 7. There is a significant interaction between sex and stroke. For males the differences between strokes mirror those in the ANOVA with the only significant difference being between breaststroke and each of the other strokes. For the females in addition to the differences seen in males, F_{max} for butterfly and front crawl is significantly lower than for backstroke The observation of significant differences between the strokes with such low subject numbers is striking.

Table 7

	Female		Male	
Stroke	20 s	60 s	20 s	60 s
Butterfly	80.72 (7.42)$^{*+}$	68.08 (5.67)$^{*+}$	104.42 (12.08)*	79.54 (9.22)*
Backstroke	127.04 (12.08)*	102.94 (6.79)*	129.36 (7.74)*	100.49 (5.91)*
Breaststroke	208.35 (17.42)$^{+}$	158.87 (13.30)$^{+}$	253.28 (12.95)	192.45 (9.88)
Freestyle	74.24 (4.41)$^{*+}$	63.39 (3.37)*	73.55 (14.56)*	58.74 (11.12)*

* significantly different than breaststroke $^{+}$ significantly different than backstroke

TABLE 7 - Adjusted means (at v = 1.49 ms^{-1}) for F_{max} from ANCOVA for sex and stroke with competition best 100 m average velocity as the covariate using the data of Mosterd & Jongbloed (1964)

Conclusion

The literature pertaining to F_{max} yields a number of patterns which will warrant continued consideration throughout the establishment of the face validity of the Max Power Model. Due to the link between F_{max} and propulsive force, of particular interest is the relationship between velocity and F_{max} and the differences in F_{max} observed among the competitive strokes. The differences in reported relationships do not appear to be linked to any systematic trait in methodology, but perhaps due to random error that occurs during data collection. While it is not possible to reach distinct conclusions concerning F_{max} due to the lack of consensus in the literature and the less than perfect link between F_{max} and propulsion, a picture of the propulsive characteristics of swimming is beginning to be developed.

Semi-tethered swimming

Introduction

Semi-tethered swimming refers to a tethered condition in which the force against the swimmer is not great enough to completely arrest the forward motion of the swimmer. Unlike fully-tethered swimming in which the entire mechanical force is exerted on the tether, a portion of the force is used to overcome the resistive forces of the water which prevent the individual from moving forward (Equation 1).

Equation 1

$F_{total} = F_{load} + F_{res}$

Semi-tethered swimming is accomplished in one of two ways. In the first method, the swimmer is allowed to swim at a set velocity by the tether and the force in excess of the resistive forces of the water is measured at the tether. In the second method, the force of the tether, 'the external load', is set and the velocity of the swimmer is measured. In the later case, the portion of the force that is not used to overcome the external load is used to overcome the resistive force of the water and thus determines the velocity which can be achieved. The relationship between F_{load} and the velocity of the swimmer and the determinants and implications of this relationship will be the first topic of discussion in this section. In order to make the multiple measurements required to determine the relationship between F_{load} and velocity a replicable effort is required. The most simplistic and reliable way to insure a replicable effort is to use maximum effort trials. Hence for the purposes of this discussion and the proposed study, only maximum effort trials (regardless of the load) will be considered.

In order to quantitatively evaluate ability in semi-tethered swimming two quantities are needed, the external force (F_{load}) and the velocity of the swimmer. These two values are combined into a single measure by the determination of the power delivered to the external load (P_{load}). P_{load} is the product of the velocity of the swimmer and F_{load}. As velocity and F_{load} change, so will P_{load}. Therefore the relationship between P_{load} and the velocity of the swimmer is also important. The P_{load} vs. velocity relationship will be the second topic explored in this section.

The most basic characteristic of the P_{load} vs. velocity relationship is that P_{load} must be 0 at two velocities: during fully tethered swimming when velocity is 0 and at the point of maximum velocity (v_{max}) when F_{load} is 0. Therefore, in between 0 and v_{max} there must be an identifiable local maxima of power (P_{max}). The final point of discussion in this section will be reported values for P_{max} found in the literature.

P_{max} is a good measure of the qualities of the relationship between F_{load} and velocity and is therefore expected to have a strong relationship with the propulsive force of the swimmer (F_{prop}). Similar to F_{max}, the environmental validity of P_{max} as a direct reflection of propulsive force is compromised by the difference in the velocity of water relative to the body compared to free swimming at maximum effort. However, in the case of P_{max}, the velocity of the water relative the body is much closer to free swimming conditions. Further discussion on this topic will occur in the next section, nevertheless this is important to bear in mind for a proper perspective on the current section.

F_{load} vs. velocity

The relationship between F_{load} and velocity has only been briefly touched upon in the section on historical perspective from the work of Houssay (1912). Logically, as F_{load} increases, velocity must decrease. The shape of the relationship between F_{load} and velocity is in question . While many authors have fit a line with great success, others believe that the relationship is likely curvilinear. Regardless of the shape of the relationship, the meaning remains the same.

There are several sources which support the linearity of the relationship between F_{load} and velocity in one of three ways: the authors do not mention linearity but the data provided can be used to show linearity, the authors mention linearity but provide no empirical evidence, or the authors both mention and assess the linearity of the relationship. Houssay (1912) falls into the first category. While Houssay does not examine the relationship between F_{load} and velocity, he does present the data that he obtained in his trials. He presented raw data for 12 trials of 5 subjects in 3 different strokes, the lowest linear correlation between velocity and load is 0.94 with an average linear correlation of 0.97. Also falling in this category, in a study examining the power generated during swimming that will be discussed in detail later on in this section Costill, Rayfield, Kirwan, and Thomas (1986) present a graph, Figure 8, that shows the relationship between F_{load} and velocity also appearing to be linear.

Three additional sources mention linearity but provide no empirical evidence. The first is an abstract by Craig and Boomer (1980). Data from each of 12 male and 26 female nationally ranked swimmers as well as 9 male and 9 female swimmers on the University of Rochester swimming teams reportedly demonstrated a linear relationship which closely predicted both the F_{max} and v_{max} intercepts. Bednarik, Kugonic, Kapus, and Strojnik (1992) take the theory one step further. Using 17 subjects (no descriptive anthropometrics provided) and testing at 4 loads that cause a change in velocity of less than 15% from v_{max}, the authors concluded that not only did a linear relationship exist, but that the 'angle' of the line could be used to identify the strengths and weaknesses of the subjects. The authors identify an angle of 45 degrees as being optimal and suggest that subjects with an angle of less than 45 degrees can generate quite a bit of force, but are not exploiting "technique" to its fullest extent. For angles of greater than 45 degrees the opposite is suggested to be true. While the specific example given is somewhat meaningless in that the angle of the line depends upon the unstandardized scale of the graph, the implications of the slope of the line towards the resistive and propulsive forces is mirrored in other sources. Finally, Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2000) mention the observation of a linear relationship between F_{load} and velocity in a study focused on power measurement and conducted using 5 female competitive swimmers.

Several articles have touched on the relationship between F_{load} and velocity as a means for the determination of resistive forces during swimming (Clarys, 1978;Clarys, 1979; Kemper, Verschurr, Clarys, & Jiskoot, 1983; Shimonagata, Taguchi, & Miura, 2003). While the focus of the articles will be described in a later section, it is important to note that each of the articles identifies the relationship as curvilinear. Additional information on the curve which is fit is not presented in any of these articles. In appearance, a majority of the curves such as the one shown below in Figure 1 from Kemper, Verschurr, Clarys, and Jiskoot (1983) subjectively appear to be interpretable as linear in nature. While a full interpretation of the this graph will occur in a later section, the vertical axis of the graph represents F_{load} with negative values reflecting the load resisting the motion of the swimmer and the horizontal axis is swimming velocity.

Figure 1

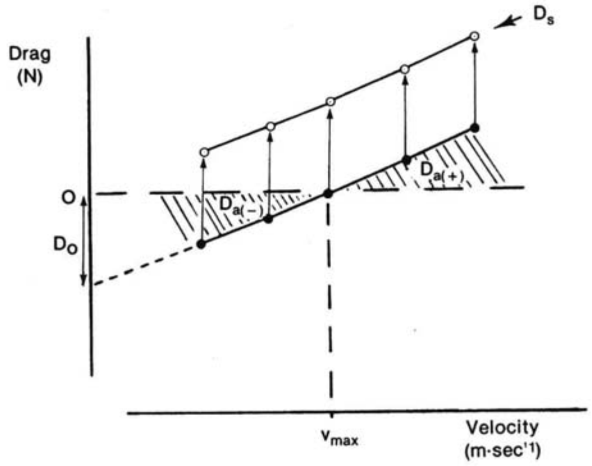


Figure 2—Determination of swimming drag D_s by extrapolation of the drag ($D_{A(+)}$) and added propulsion ($D_{A(-)}$) curve to D_0 at zero velocity.

FIGURE 1 – from Kemper, Verschurr, Clarys, & Jiskoot (1983)

The study conducted by Wirtz, Bieder, Wilke, and Klauck (1999) provides empirical data on the relationship between F_{load} and velocity, but the way in which the data is reported makes its interpretation challenging. Both male (N = 38) and female (N = 22) swimmers (age = 17.28 ± 3.65 years, mass = 68.3 ± 11.6 kg, height = 175 ± 10 cm) with best 50 m times of 27.97 ± 2.31 seconds were tested over a series of 7.5 m maximal effort semi-tethered front crawl swims. Briefly, the trials began with a 7.5 m free swim after which the load of the tether was successively, incrementally increased until the swimmer could no longer complete the 7.5 m swim in less than 10 seconds ($v < 0.75$ m/s). It appears that this normally provided approximately 5 points to construct the relationship of F_{load} vs. swim time. Herein lies the difficulty, the authors never convert swim time to velocity. Thus, the group data they present on the linearity of the graph of F_{load} vs. time should imply a logarithmic relationship between F_{load} and velocity. However, as part of the methodology, trials involving larger loads were removed from the analysis based upon the ability of the linear fit to accurately predict the intercept of the graph representing the free swimming time for 7.5 m. While the authors report linear correlations between 0.94 and 0.99 for all individuals and correlations of 0.89, 0.92, and 0.88 for three groups separated based upon ability, the linearity and the correlations are not representative of all values of F_{load} only those in the lower range. While the authors attribute the deviation from the regression line to changes in the metabolic source of the energy during the longer duration of the trials with higher loads, this seems unlikely being that the trials were all less than 10 seconds. Instead, it seems more likely (and fitting with previous literature) that the relationship between F_{load} and time is not linear. Figure 2 is a theoretical representation of sample data similar to that which would have been seen in the study of Wirtz, Bider, Wilke, and Klauk. Figure 2 assumes a linear relationship between F_{load} and velocity and then sets to examine the relationship of F_{load} to time based upon the procedure of Wirtz, Bider, Wilke, and Klauk. This procedure calls for the elimination of points which cause the predicted value for the 7.5 m free swim to deviate from the measured value by more than 0.1 s. In this case the measured value is set to 4.17 s and only the first four points at 7.5 N spacing are used in order for the linear prediction to fit the criteria. This results obtained using this theoretical model are similar to the reported values in the article. It can be seen, however, that the excluded data is far from linear. Thus a linear model, or a nearly linear model, of the F_{load} vs velocity curve does not run contrary to the reported results. Because of systematic data selection procedures, the results of the study of Wirtz, Bider, Wilke, and Klauk do not help to further knowledge of the relationship between F_{load} and velocity.

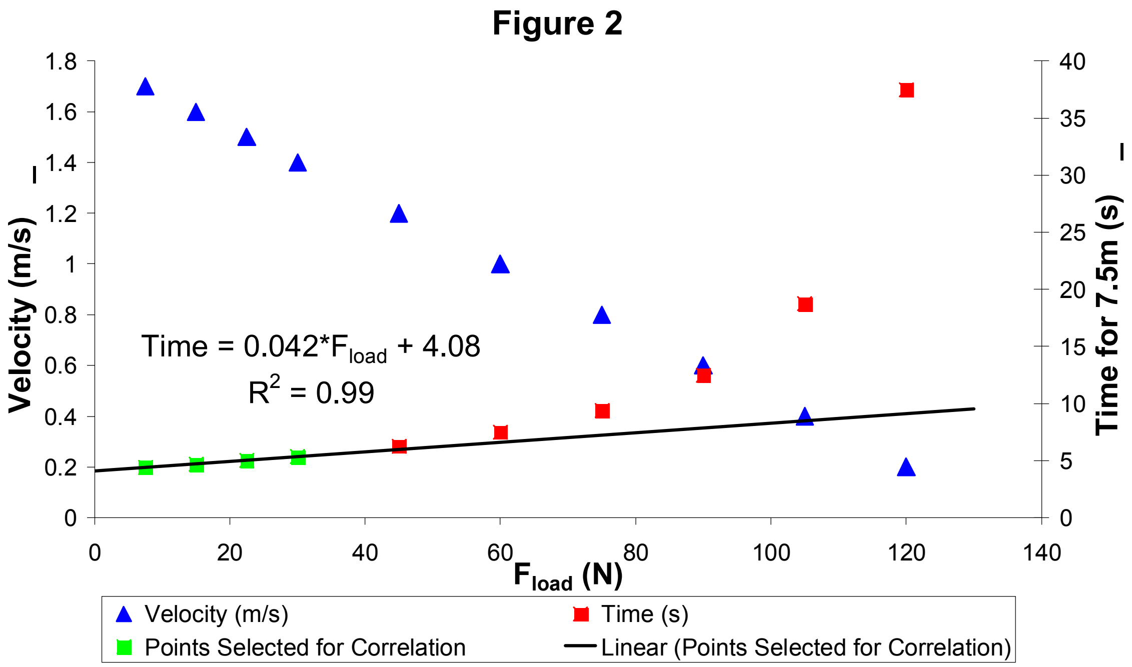


FIGURE 2 - A demonstration of the consistency of linearity between time and F_{load} reported by Wirtz, Bider, Wilke, & Klauk (1999) with linearity of velocity and F_{load}

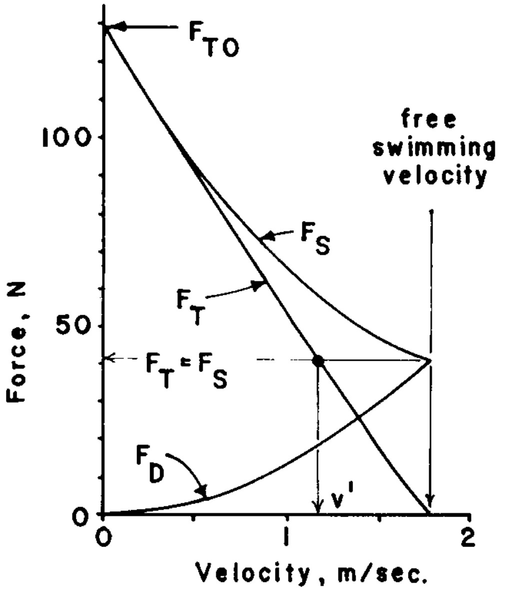
Wirtz, Bider, Wilke, and Klauk (1999) also examine the implications of swimming ability on the results of semi-tethered swimming. The subjects were separated into three groups based on v_{max} with group means of 1.85 ± 0.08, 1.68 ± 0.04, and 1.56 ± 0.03 m/s. After calculating the regression lines for time vs. F_{load}, the lines for each of the three groups were reported as being different based upon a lack of overlap of the 95% confidence intervals of the lines. The authors noted that the ability of the subjects appeared to be related to the slope of the lines pairing swimmers with greater ability with smaller slopes. They also make the assertion that the smaller the slope of the line the greater the “technical ability” of the subject. They contrast this to the “physical performance" of the subject. The terms technical ability and physical performance refer to the resistive and propulsive components of velocity production respectively. To compare this with the assertion by Bednarik, Kugonic, Kapus, and Strojnik (1992) that a smaller negative slope on a graph of F_{load} vs. velocity is indicative of lower resistive forces, the differences between graphs with time and velocity as the independent variable must once again be taken into account. For Wirtz, Bider, Wilke, and Klauk a small slope is a result of small decreases in time, and therefore velocity, as F_{load} increases from 0. This is equivalent to a smaller negative slope on a graph of F_{load} vs. velocity. Thus it can be seen that both groups of authors are drawing the same conclusion despite basing them on different analyses.

Shimonagata, Taguchi, Tabu, Ohshiro, and Miura (2002) support the conclusion of linearity with empirical data. Using collegiate female swimmers (N = 8, mass = 57.33 ± 5.82 kg, height = 164 ± 4 cm) with an average competitive best velocity of 1.61 ± 0.08 m/s in the 100 m front crawl, Shimonagata et al. measured velocity during maximal efforts over 25 m with $F_{load} = 0$ and four other values. The relationship between F_{load} and velocity showed a significant linear correlation ($p < 0.05$) for every subject with R = 0.97 ± 0.02.

Theoretical Relationships

Using a linear or 'close-to-linear' relationship between F_{load} and velocity, the theoretical relationships between the F_{load}, the resistive force of the water (F_{res}), and the propulsive force of the swimmer (F_{prop}) can now be examined. The basis for the theoretical model to be used was substantiated by Martin, Yeater, and White (1981) as can be seen in the similarity between Figure 3 (from Martin, Yeater, and White) and Figure 4, constructed as the basis for further discussion.

Figure 3



Theoretical relationships of F_T (the force of the external load; F_{load}), F_S (the propulsive force of the swimmer; F_{prop}), and F_D (the resistive force of the water on the swimmer; F_{res}) to velocity from Martin, Yeater, & White (1981)

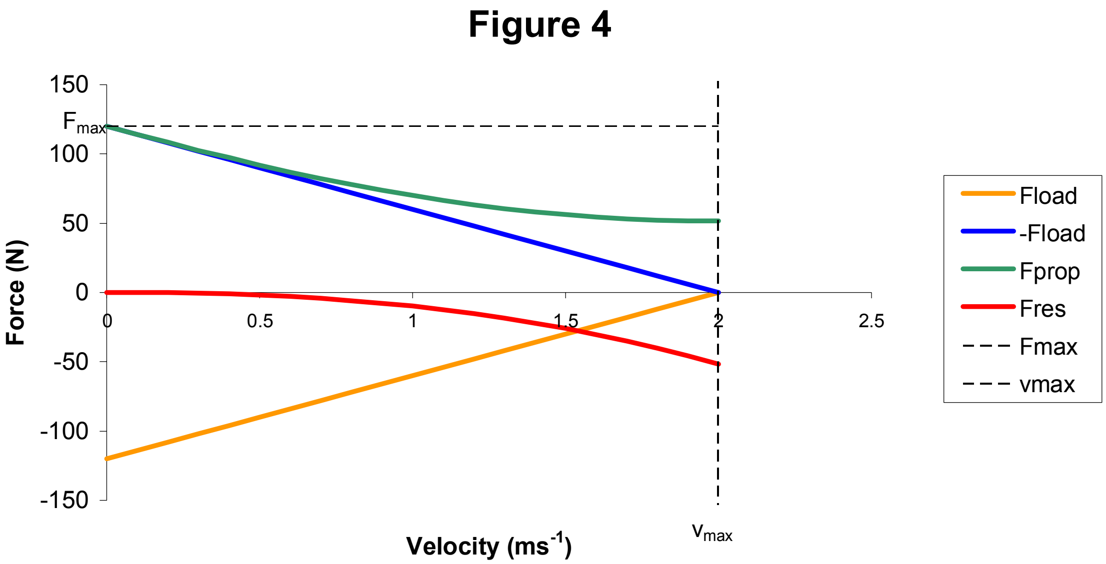


FIGURE 4 - Theoretical relationships of the force of the external load (F_{load}), the propulsive force exerted by the swimmer on the water (F_{prop}), and the resistive force of the water on the swimmer (F_{res}) to velocity based on the linearity of F_{load} vs. velocity and the approximate proportionality of F_{res} to velocity squared

It is known from Newton's Third Law that at a constant velocity (as each semi-tethered trial is assumed to be) the sum of the forces must be zero. As the three forces that exist are the force of the tether (F_{load}), the resistive force of the water on the swimmer (F_{res}), and the propulsive force of the swimmer on the water (F_{prop}) they are related as seen in Equations 2 and 3 at each semi-tethered velocity.

Equation 2

$$0 = F_{load} + F_{res} + F_{prop}$$

Equation 3

$$-F_{load} = F_{res} + F_{prop}$$

Of these three forces, only F_{load} can be directly measured. For the purpose of simplicity, the relationship between F_{load} and velocity will be assumed to be linear, although this will not effect any of the conclusions drawn as will be discussed later. At 0 velocity, $F_{res} = 0$ and thus $-F_{load} = F_{prop}$. Therefore for 0 velocity only, F_{prop} can be measured and as it is at its maximum value for any velocity is referred to as F_{max}. As previously mentioned, F_{prop} decreases as velocity increases because the water begins to move underneath the body more quickly and the ability to generate propulsive force decreases. Changes in efficiency may also be a source of the decrease in F_{prop} with increases in velocity. In any event, at any velocity greater than 0, neither F_{prop} nor F_{res} can be directly measured.

With the assumption that the affect of the change in water velocity on the ability of the swimmer to produce force is relatively consistent between swimmers and in different styles of swimming, the slope of the line representing F_{load} can be viewed as an indication of the rate at which the resistive force is increasing. The greater the slope of the line, the greater the rate at which the resistive forces are developed with an increase in velocity. This can be seen in Figure 5, in which the F_{max} remains the same, but an increase in F_{res} at each velocity will cause the slope of the F_{load} line to increase and the v_{max} to decrease.

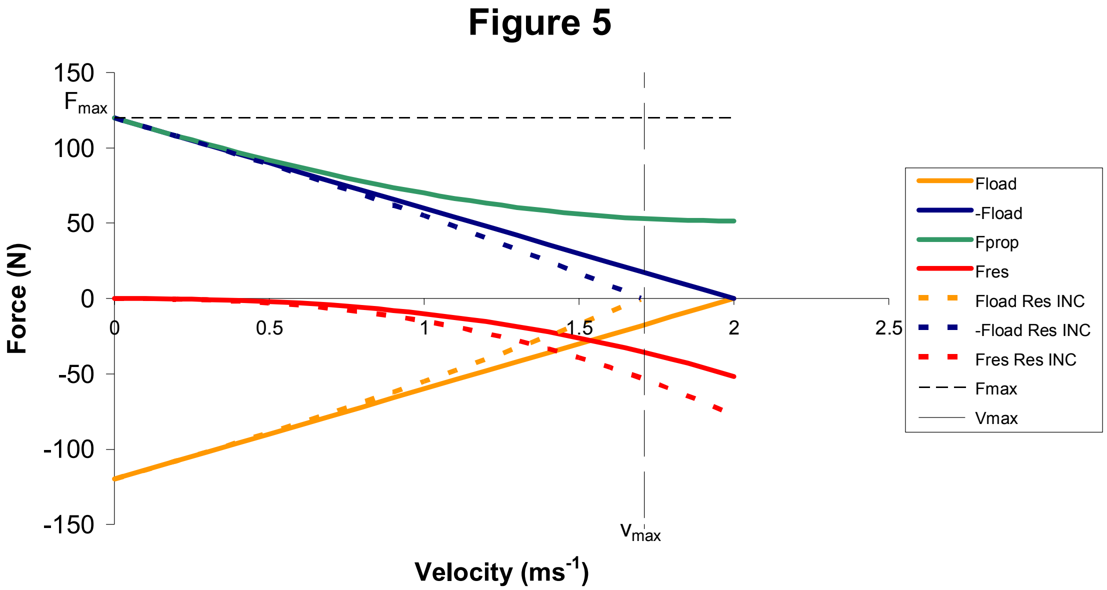


FIGURE 5 - Theoretical effect of an increase of F_{res} on F_{max}, v_{max}, and the relationship of F_{load} to velocity

Just as the slope of the line is an indication of the resistive forces on the swimmer, the intercept (F_{max}) of the line is indicative of the propulsive forces of the swimmer. If the resistive forces remain the same, but the propulsive forces increase, then the slope of the F_{load} line will not change, F_{max} will increase, and the v_{max} will increase as exhibited in Figure 6.

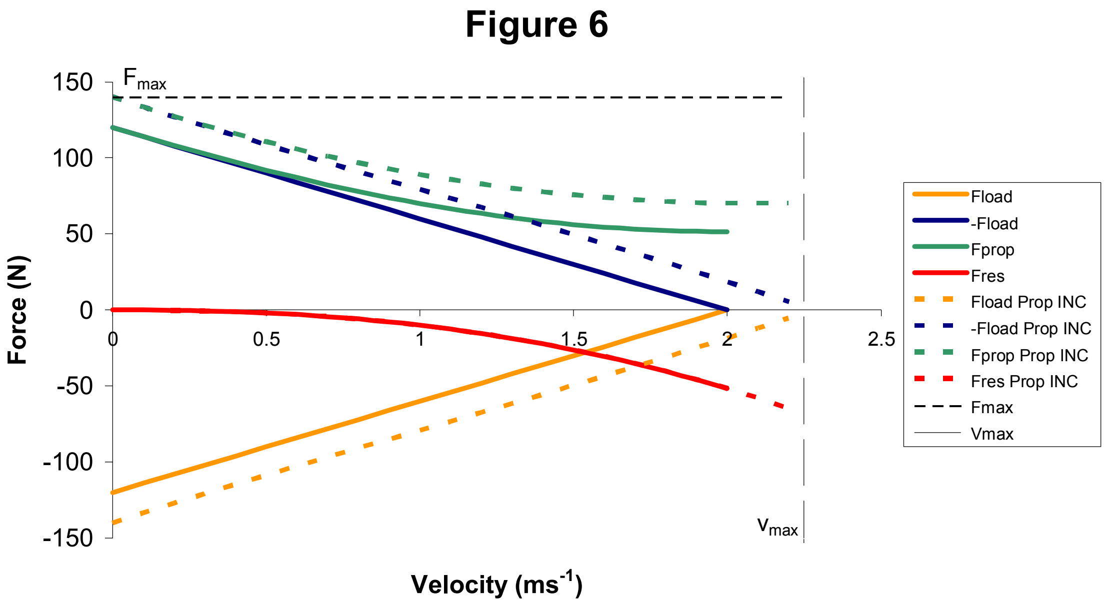


FIGURE 6 - Theoretical effect of an increase in F_{prop} on F_{max}, v_{max}, and the relationship of F_{load} to velocity

The true linearity of the F_{load} vs. velocity relationship has some implications towards the representation of the propulsive and resistive forces by the intercept and the slope of the line respectively. If the relationship were truly linear, it could be concluded that the rate of decline in the ability to create propulsive force is approximately the same as the rate of increase in resistive forces. This in itself is an interesting observation in that it may imply that individuals who experience large resistive forces during swimming also tend to be those for whom propulsive forces decrease at the greatest rate as the water moves faster under the body. More likely it implies that our model is simplistic and that the slope and the intercept of the graph can not be considered independent of one another. Thus it is unlikely that the slope of the F_{load} vs. velocity curve solely represents the resistive forces and that the intercept solely represents the propulsive forces. The inexplicable linking of the forces necessitates use of and suggests a mechanistic relationship of velocity with a quantity which is a combination of the slope and the intercept.

P_{load} vs. velocity

The power delivered to the external load (P_{load}) may be the appropriate quantity to fill the place of a combined measure of the slope and intercept of the F_{load} vs. velocity line. P_{load} is the product of F_{load} and velocity. Assuming that the relationship between F_{load} and velocity is linear, P_{load} can be determined as a function of velocity.

Derivation 1

$F_{load} = F_{max} - (F_{max}/v_{max})*v$

$P_{load} = F_{load}*v$

$P_{load} = (F_{max} - (F_{max}/v_{max})*v)*v$

$P_{load} = F_{max}*v - (F_{max}/v_{max})*v^2$

Figure 7

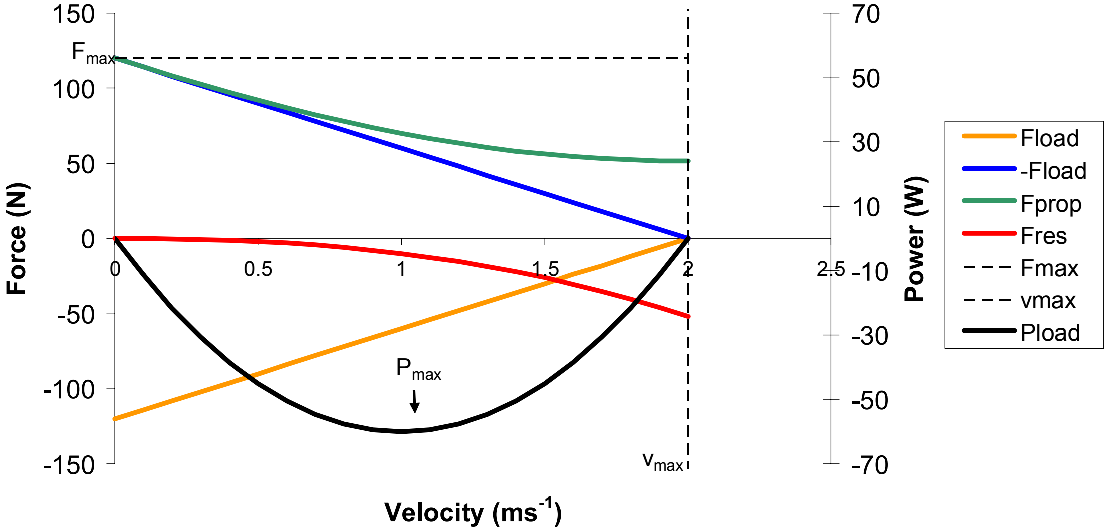


FIGURE 7 - Theoretical relationships of F_{load}, F_{prop}, and F_{res} to velocity showing the corresponding power delivered to the external load (P_{load}) and its local maxima (P_{max})

Figure 8

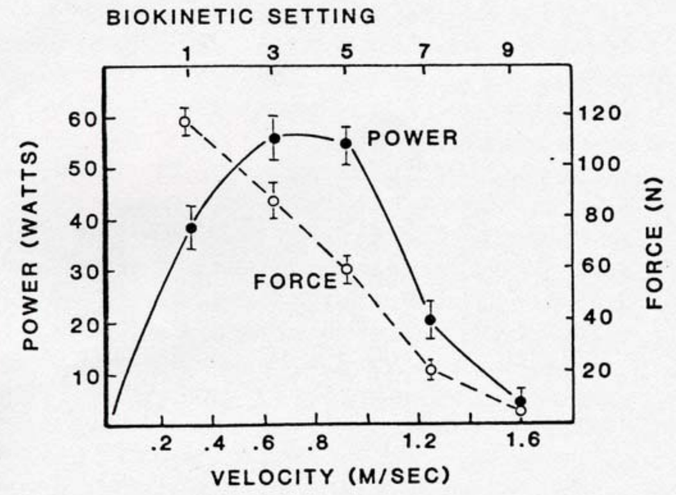


Figure 3. Illustrations of the relationship of tethered swimming power and force to the tethered front crawl velocity. The biokinetic settings are those predetermined settings on the biokinetic apparatus.

FIGURE 8 – Experimental verification of the local maxima of power delivered to an external load (Pmax) from Costill, Rayfield, Kirwan, & Thomas (1986)

This is a second order polynomial function which forms a parabola. The width and height of the parabola are determined by the slope and intercept of the F_{load} vs. velocity line and therefore are determined by the resistive and propulsive forces experienced or generated by the swimmer. Because the graph of P_{load} vs. velocity is a parabola, a maximum value for P_{load} exists and can be defined as P_{max}. Based upon the direction of motion chosen as positive, P_{max} may also be viewed as a local minima as in Figure 7. Costill, Rayfield, Kirwan, and Thomas (1986) have published a reproduction of the P_{load} vs. velocity curve from actual data as seen in Figure 8. Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2002) also found a parabolic relationship between P_{load} and velocity even reporting the best fit function for one subject ($P_{load} = -86.31v^2 + 136.25v$). While only two studies reproduce and describe an actual P_{load} vs. velocity curve many merely assume that the relationship must have a local maxima since P_{load} is equal to 0 at both v_{max} (when F_{load} is 0) and 0 velocity (Craig & Boomer, 1980; Hopper, 1981; Hopper Hadley, Piva, & Bambauer, 1983; Johnson, Sharp, & Hedrick, 1993; Klentrou & Montpetit, 1991; Shimonagata, Taguchi, & Miura, 2003; Shimonagata, Taguchi, Taba, Ohshiro, & Miura, 2000). These studies report values for P_{max} without examining the nature of the relationship between P_{load} and velocity.

By setting the first order differentiation of the $P_{load}(v)$ function equal to zero, the value of velocity at which P_{max} occurs can be determined in terms of F_{max} and v_{max}.

Derivation 2

$dP_{load}/dv = F_{max} - (F_{max}/v_{max})*2v$

letting $dP_{load}/dv = 0$

$0 = F_{max} – (F_{max}/v_{max})*2v$

$F_{max} = (F_{max}/v_{max})*2v$

$v_{max} = 2v$

$½v_{max} = v$

Thus in order to find a value for P_{max}, we can substitute $v = ½v_{max}$ back into our equation to determine P_{load}.

$P_{load}(½v_{max}) = P_{max} = F_{max}*(½v_{max}) – (F_{max}/v_{max})* (½v_{max})^2$

$P_{max} = ½F_{max}v_{max} -¼F_{max}v_{max}^2/v_{max}$

$P_{max} = ½F_{max}v_{max} – ¼F_{max}v_{max}$

$P_{max} = ¼F_{max}v_{max}$

Hence, it can be seen that P_{max} has a relationship dependent upon both F_{max} and v_{max} and therefore it is dependent on both the slope, $-F_{max}/v_{max}$, and the intercept, F_{max}, of the F_{load} vs. velocity graph. $P_{max} = ¼\text{intercept}^2/\text{slope}$. The value and placement of P_{max} derived are dependent upon the linearity of the F_{load} vs. velocity relationship. Deviation from this linearity will also cause deviation from the value and placement of P_{max}.

Measurement of P_{max}

The maximum power delivered to an external load (P_{max}) has been measured with a wide variety of different experimental setups by a number of different research groups (Craig & Boomer, 1980; Costill, Rayfield, Kirwan, and Thomas, 1986; Hopper, 1981; Hopper Hadley, Piva, & Bambauer, 1983; Johnson, Sharp, & Hedrick, 1993; Klentrou & Montpetit, 1991; Shimonagata, Taguchi, & Miura, 2003; Shimonagata, Taguchi, Taba, Ohshiro, & Miura, 2000; Shimonagata, Taguchi, Taba, Ohshiro, and Miura, 2002). Before reviewing the literature, it is important to distinguish P_{max} from values of power reported in the literature that are estimates of 1) the power generated during free swimming or 2) the total power generated during tethered swimming and not 3) the power delivered to an external load. These alternate expressions for power are often based upon a value of resistive force determined by the authors. The power values found in these circumstances will be discussed as the resistive force determination using ARS is discussed in a later section. Determinations of P_{max} fall into two categories. P_{max} is most thoroughly determined by running each subject through a series of semi-tethered swims and calculating P_{max} from the highest P_{load} observed for each individual. To save time, P_{max} may also be estimated from testing at a single velocity determined in a subgroup to elicit the highest P_{load}. This method involves only a single swim per subject and thus saves time, but compromises the accuracy of the measurement when compared to a more thorough determination of the whole P_{load} vs. velocity curve. Use of a single trial also makes comparison with other studies difficult as the velocity chosen is highly dependent on the ability of the subjects.

When comparing P_{max} values, there are several confounding variables to bear in mind. These variables resemble those considered during the discussion of F_{max} values: ability of the subjects, duration of the swim, and the stroke swum. Only one study examines the effects of different competitive strokes. Hence unless mentioned otherwise, reported P_{max} values refer to front crawl.

Several different research groups have determined P_{max} by determining the peak P_{load} for each individual. In addition to the confounding variables that exist in all determinations of P_{max}, this method has a distinct confounding variable: the step size of the increase in load, or velocity. In a sense, this is the resolution of the picture of the power curve. Using too great of a step size may lead the largest to value of P_{load} to be off of the actual peak of the curve and therefore cause the investigator to identify the a value for P_{max} which is lower than the true value. Thus it is important to note the step size for the load in each of the studies. The first published record of P_{max} was from Craig and Boomer (1980). As this was an abstract, values for P_{max} are not published and the methodology is not elucidated. This was followed by an abstract and an article by Hopper (1981) and Hopper, Hadley, Piva, and Bambauer (1983) respectively. Hopper introduces the use of a weight and pulley system and clearly defines his methodology in the article (1983). The load is increased by 2 lbs (8.92 N) per trial (correcting for the mechanical advantage) which leads to between 3 and 10 points along the P_{load} vs. velocity curve. Hopper introduces an element of efficiency into the measurements in defining Power Per Stroke (PPS) which is defined as P_{max} divided by the number of strokes taken over the trial. As Hopper found that PPS is a better predictor of performance than P_{max}, both sources choose to report only values for PPS and not P_{max} (Hopper, 1981; Hopper, Hadley, Piva, and Bambauer, 1983). Thus the values can not be used for comparison and do not directly relate to the focus of the proposed study.

Continuing chronologically, in 1993 Johnson, Sharp, and Hedrick published the first study using this methodology that provided values of P_{max}. Johnson, Sharp, and Hedrick tested male swimmers (N = 29 age = 18 ± 2 years, mass = 76.9 ± 9.3 kg, height = 181 ± 6 cm) with v_{max} values of 2.04 ± 0.11 m/s as evaluated by a maximal 25 yd (22.86 m) swim timed from when the feet left the wall to when the hands touched the opposite wall. P_{load} was calculated with loads of 4.9, 14.7, 30.4, 46.1, 60.8, 76.5, and 91.2 N for a step size of approximately 15 N, about double that of Hopper. The load was provided by a Power Rack made by Total Performance with a travel distance of approximately 12.5 yards (11.43 m). P_{max} was found to be 85 ± 23 W.

Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2000), Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2002), and Shimonagata, Taguchi, and Miura (2003) use the same equipment and methodology in the determination of P_{max}. Instead of lifting a stack of weights, swimmers towed an object that provided additional drag forces. This object was calibrated for force over a full range of velocities and could be configured to provide 4 different levels of F_{load}. Thus the resolution of these measurements was low. The swimmers swam with the object for 25 m at maximal effort and the time for the last 10 m was used in the calculation of power. Measurement of v_{max} was made using the same method with free swimming. Shimonagata et al. (2000) reported a P_{max} of 60.90 ± 4.02 W for a corresponding v_{max} of 1.64 ± 0.04 m/s in a group of 5 female competitive swimmers. Shimonagata et al. (2002) found a P_{max} of 52.75 ± 13.15 in a group of 8 female competitive swimmers corresponding to a v_{max} of 1.60 ± 0.07 m/s. Shimonagata, Taguchi, and Miura tested both male (N = 5, age = 21.6 ± 1.1 years, mass = 69.4 ± 3.7 kg, height = 177 ± 5 cm) and female (N = 6, age = 21.3 ± 1.0 years, mass = 52.8 ± 3.4 kg, height = 160 ± 5 cm) competitive swimmers. The males and females produced P_{max} = 100.7 ± 11.5 W and 36.5 ± 11.2 W corresponding to v_{max} = 1.77 ± 0.08 m/s and 1.35 ± 0.21 m/s respectively.

Finally, White, Stager, Tanner, Simmons, and Naganobori (2003) and White and Stager (2004) used identical methodology to one another. In this case a modified Power

Rack was used and P_{load} was calculated using the time over a 10 m distance starting a short distance from the wall in order to minimize the effect of the push off. v_{max} was measured using a 15yd (13.72 m) swim timed using head position and also beginning a short distance from the wall. F_{load} began at approximately 20 N and increased by approximately 2 N per trial for a very high resolution of the power curve. Neither abstract presents absolute values for P_{max}.

Three studies from two different labs represent the form of P_{max} determination in which a single velocity is used to estimate P_{max} for the entire group of subjects. Costill, Rayfield, Kirwan, and Thomas (1986) measured P_{load} using a modified biokinetic swim bench. The swim bench was set to allow the swimmer to swim at a set velocity and the force in the line was measured for a number of different velocities. Testing was conducted using male (N = 46, mass = 75.6 ± 1.4 kg, height = 180.8 ± 3.1 cm) and female (N = 30, mass = 63.6 ± 1.8 kg, height = 164.5 ± 2.4 cm) collegiate swimmers between 17 and 22 years of age. A subsample of 10 men was tested for P_{load} for a 12 s effort at 0.323, 0.641, 0.954, 1.263, and 1.605 m/s. Each subject reached P_{max} at 0.954 m/s. v_{max} was determined by use of a 25yd (22.86 m) maximal effort swim and was found to be 1.97 ± 0.02 m/s and 1.74 ± 0.02 m/s for males and females respectively. Theory predicts that P_{max} should occur at $\frac{1}{2}v_{max}$. For the males the average velocity at P_{max} was achieved at the closest velocity setting to $\frac{1}{2}v_{max}$ supporting the theory and the linearity of the F_{load} vs. velocity relationship. The females were tested at 0.62 m/s. The group for which this value was established was unclear and the authors do mention that some of the swimmers achieved higher power outputs at lower velocities. Using this methodology P_{max} was found to be 43.6 ± 3.3 W for the males and 25.7 ± 1.8 W for the females.

Similar to this approach, Klentrou and Montpetit (1991) measured P_{load} at 1.1 m/s for male Canadian age group (age 16.8 ± 2.2 years) swimmers divided by specialty into 100 m (N = 12, mass = 69.8 ± 5.4 kg, height = 177.9 ± 6.1 cm) and 400 m (N = 13, mass = 65.8 ± 6.7 kg, height = 174 ± 7.5 cm) freestyle specialists. P_{load} at 1.1 m/s was assumed to be P_{max} and testing was conducted using a modified cybex machine over a 15 m maximal effort. While the average velocity over a 400 m swim was not significantly different between the two groups (1.44 ± 0.06 m/s vs. 1.45 ± 0.04 m/s), a t-test showed that the 100m specialists had a significantly ($p \leq 0.05$) larger P_{max} than the 400 m specialists (76.9 ± 11.3 W vs. 67.1 ± 12.8 W respectively).

In order to compare the values for P_{max} obtained from different sources, consider Table 8 and Figure 9. Based upon the identical testing procedures used by Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2000), Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2002), and Shimonagata, Taguchi, and Muira (2003), it appears that v_{max} is related to P_{max}. Multiple groups tested both male and female swimmers and in each case the males had higher P_{max} and v_{max} values. P_{max} values for Costill, Rayfield, Kirwan, and Thomas (1986) and Johnson, Sharp, and Hedrick (1993) appear to be in general lower than those of the Shimonagata group. In comparison with the three articles with Simonagata as the lead author, the deviation in values of Costill et al. can be explained by three possible methodological differences. First, Costill et al. do not determine the peak of the P_{load} vs. velocity curve for each subject. Any error induced in P_{max} from this procedure will produce a lower P_{max} than expected. Second, the procedure of Costill et al. requires that the athlete begin each trial from a stationary float in the water. The Shimonagata group begins the recorded period after the swimmer has already reached a maximum effort and constant velocity. This difference may bias the Shimonagata group P_{max} values to be larger in relation to the Costill et al. values. The third methodological difference is seen not only between Costill et al. and the Shimonagata group, but also between Johnson et al. and the Shimonagata group. Both Johnson et al. and Costill et al. measure v_{max} as the average velocity over a 25yd (22.86 m) swim from the time the feet leave the wall until the time the hand touches the other end of the pool. The Shimonagata group measures v_{max} as the average velocity over the last 10 m of a 25 m swim presumably started and ended using hand position. The v_{max} of the Shimonagata group does not include a push off or the decrease in distance of the actual swim caused by beginning the time at the feet and stopping at the hand. Therefore values of v_{max} in the Shimonagata group are lower relative to those of both Costill et al. and Johnson et al. causing a relative leftward position of the Shimonagata points on Figure 9. These three sources of methodological difference could account for the deviations in the P_{max} values seen in different research groups.

Table 8

Author	v_{max} (m/s)			P_{max} (W)		
Johnson Males	2.04	±	0.11	85	±	23
Shimonagata (2000) Females	1.64	±	0.04	60.9	±	4.02
Shimonagata (2002) Females	1.60	±	0.07	52.75	±	13.15
Shimonagata (2003) Males	1.77	±	0.08	100.7	±	11.5
Shimonagata (2003) Females	1.35	±	0.21	36.5	±	11.2
Costill (1986) Males	1.97	±	0.02	43.6	±	3.3
Costill (1986) Females	1.74	±	0.02	25.7	±	1.8

TABLE 8 - Means and standard deviations for the maximum power delivered to the external load (P_{max}) and the corresponding maximum free swimming velocity (v_{max}) of the subject population

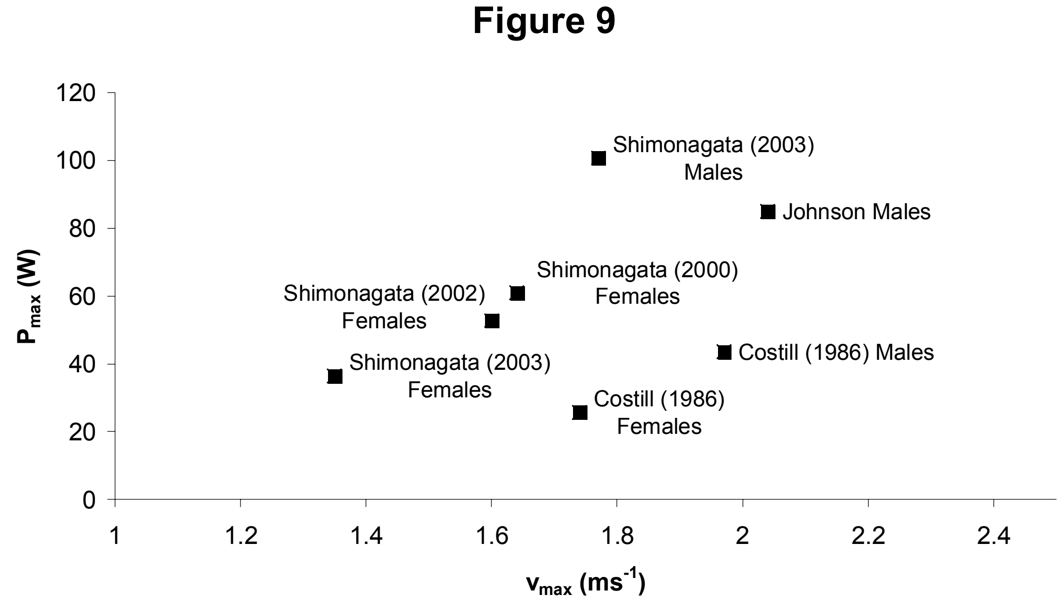


FIGURE 9 - Graphical representation of the means for P_{max} and v_{max} found in the literature

Building on the methodology of Costill, Rayfield, Kirwan, and Thomas (1986), D'Acquisto and Costill (1998) present the only values of P_{max} for a stroke other than front crawl. D'Acquisto and Costill tested both male (N = 7, age = 19.7 ± 1.5 years, mass = 75.0 ± 8.0 kg, height = 181.9 ± 8.2 cm) and female (N = 10, age = 19.1 ± 1.1 years, mass = 62.8 ± 6.0 kg, height = 166.4 ± 9.4 cm) well trained college breaststroke swimmers. Testing was done at 0.9 m/s for comparison with the previous work of Costill on freestyle swimmers. The testing followed the same protocol, but in this case the resistive device used was a modified Cybex machine. Using t-tests, the authors found significant differences ($p<0.05$) between males and females in both v_{max} and P_{load} at 0.9 m/s (1.53 ± 0.11 m/s, 64.45 ± 17.63 W; 1.26 ± 0.17 m/s, 27.33 ± 8.64 W). While these values for P_{load} are useful in terms of comparison with the front crawl values of Costill, Rayfield, Kirwan, and Thomas it is unlikely that they can be considered measures of P_{max} as theory predicts that P_{max} should occur at approximately 0.76 m/s for males and 0.62 m/s for females based upon v_{max}. In comparison with front crawl from the same lab, breaststroke has larger values of P_{max} despite having smaller v_{max} values. This is true despite the likelihood that the values of P_{load} at 0.9 m/s are not true values of P_{max} for breaststroke. This comparison alone is not conclusive, however it does agree with the conclusion of a larger F_{prop} for breaststroke than front crawl reached dealing with F_{max}.

Conclusion

Use of semi-tethered swimming makes several important advancements over the use of fully tethered swimming. Semi-tethered swimming moves from solely examining propulsive forces to offering a glimpse of the resistive forces experienced during swimming. Semi-tethered swimming also offers greater environmental validity in the determination of propulsive force as it can be used to evaluate propulsive force at conditions of greater than 0 velocity. P_{load} combines the information provided by both the slope and the intercept of the F_{load} vs. velocity graph into a single quantity. P_{max} allows for the best standard of comparing values of P_{load}. As seen in a comparison of different studies, P_{max} depends upon v_{max}. Alluding to the next section, the nature of this relationship is the key to creating a method of quantitatively evaluating differences in the resistive and propulsive forces in swimming.

Relationships between maximum power output and velocity or performance

Introduction

The relationship between maximum power delivered to an external load (P_{max}) and maximum velocity (v_{max}) is the basis of the Max Power Model (MPM) for evaluating resistive and propulsive forces during swimming. The goal of many of the studies discussed here has been to determine F_{res} and F_{prop} during free swimming (represented by the right side of Figure 4). The goal of the proposed study is not to assign a numerical answer to this question, but to provide a quantitative way to evaluate resistive and propulsive forces during different forms of swimming relative to one another. The hypothesis is that this relative comparison can be quantified by comparing the P_{max} vs. v_{max} curves in group data for different types of swimming. The next section will outline the literature pertaining to the relationship of P_{max} and v_{max} and the following section will discuss the way in which the relationship will be used to evaluate resistive and propulsive forces.

Literature Review

Literature on the relationship between P_{max} and v_{max} is similar to that of F_{max} and v_{max} in that it primarily consists of linear correlations with little attention to the true shape of the curve. In general large linear correlations are seen between P_{max} and v_{max}. Insight on the linearity of the relationship can be seen in sources mentioning disproportionate differences in P_{max} and v_{max}. Unless otherwise mentioned all studies were conducted using front crawl.

First the evidence regarding the significance of a linear correlation between P_{max} and v_{max} will be offered. Shimonagata, Taguchi, Taba, Ohshiro, & Miura (2000) found a non-significant linear correlation of $R = 0.35$ between P_{max} and v_{max}. This small correlation may be attributed to a small subject number (5) and the similarity of the subjects as demonstrated by the standard deviations of both the P_{max} and v_{max} measures in Table 8. However, using a different subject population, Shimonagata, Taguchi, Taba, Ohshiro, and Miura (2002) later report a significant ($p < 0.01$) linear correlation ($R = 0.87$) between P_{max} and v_{max}. Subsequently, a larger, more diverse population examined by the same group also yielded a significant correlation of $R = 0.92$ (Shimonagata, Taguchi, & Miura, 2003). Johnson, Sharp, and Hedrick (1993) found a linear correlation of $R = 0.87$ between P_{max} and v_{max}. They also examined the relationship between P_{load} at two standardized loads and v_{max}. P_{load} with an $F_{load} = 76.5$ N correlated significantly with v_{max}, $R = 0.84$. For a smaller load ($F_{load} = 14.7$ N) the correlation between P_{load} and v_{max} was $R = 0.88$. The correlations of Johnson, Sharp, and Hedrick give a closer basis of comparison for the linear correlations to P_{load}s for which velocity was held constant.

Costill, Rayfield, Kirwan, and Thomas (1986) found a significant linear correlation between v_{max} and P_{load} at a velocity 0.9 m/s of $R = 0.84$. Similarly, D’Acquisto and Costill (1998) examined the relationship between P_{load} at 0.9 m/s and v_{max} for breaststroke in males and females separately and found linear correlations of 0.64 (non-significant) and 0.87 respectively. Continuing with another constant velocity study, Klentrou and Montpetit examined correlative between P_{load} at a velocity of 1.1 m/s and performance. Neither the best competition time in the 100 m front crawl (for 100 m specialists) or the 400 m front crawl (for 400 m specialists) was found to have a significant correlation to P_{load} at 1.1m/s. The methodology and therefore the results of this study can be called into question based upon the low correlation ($R = 0.58$) between the velocity during a maximal effort 400 m swim and best competition time in the 400 m for 400 m specialists. This low correlation means that the time swum for the 400 m in testing explained only 34% of the variance in competition best time of the athlete and suggests, at minimum, that the competition best times were not a good indication of the swimmers abilities at the time of the tests.

Evidence for a non-linear relationship between P_{max} and v_{max} can be seen in a couple of studies (Costill, Rayfield, Kirwan, & Thomas, 1986; Craig & Boomer, 1980). Costill, Rayfield, Kirwan, and Thomas (1986) found that following 8 weeks of swimming and strength training, P_{max} increased 9.6% while v_{max} increased only 4.0%. This difference could be attributed to either changes towards lower swimming efficiency or a non-linear relationship between P_{max} and v_{max}. Craig and Boomer (1980) note that P_{max} for females was 30% less than males while v_{max} was only 10% less. While the authors suggest this to be indicative of a difference in the P_{max} to v_{max} relationship between males and females, it could be a further indication that the P_{max} vs. v_{max} relationship is not linear.

The existence of a strong relationship between P_{max} and v_{max} seems clear. Evidence suggests that despite the strong linear correlations, the relationship may be best fit by another function. The strength of the relationship between P_{max} and v_{max} shows that both variation between individuals in the same style of swimming and random error are relatively small. This is crucial when attempting to evaluate the differences in this relationship between different styles of swimming.

Interpretation and Proposed Use

The section dealing with semi-tethered swimming showed the link between the maximum power delivered to an external load (P_{max}) and the resistive and propulsive forces experienced during swimming. The strength and shape of the relationship between P_{max} and v_{max} has also been established. The ability to combine these two parts of the puzzle to quantify the differences in swimming styles is the province of the Max Power Model (MPM) and has yet to be fully elucidated. This section will explain both how the MPM purports to define the differences and will present pilot information on the four different strokes as an example.

Logically if two different styles of swimming are producing two different P_{max} values at the same v_{max}, then the style with the lower P_{max} should be experiencing less resistive force. It can be argued that the same is true of F_{max}. While this may be true, use of P_{max} is better for two reasons. First, as seen in information presented earlier, measurement of F_{max} tends to have a relatively large amount of random error associated with it which make determination of the relationship between F_{max} and v_{max} difficult. Second, the main criticism of F_{max} is that it is environmentally invalid in that the water below the body is not moving. As seen in Derivation 2, the measurement of P_{max} should theoretically occur when the swimmer is moving at $\frac{1}{2}v_{max}$ which while not a perfect mimic of free swimming is a dramatic improvement over the conditions at F_{max}.

If in the relationship between P_{max} and v_{max} the differences between individuals swimming the same style is markedly less than the differences between the same individual swimming in two different styles, then the differences in resistive forces between two different styles of swimming can be quantified by a comparison of the P_{max} required to reach a certain v_{max}. To generalize a bit, the placement of the curves on a graph of P_{max} vs. v_{max} can be quantified and curves which require greater values of P_{max} at any v_{max} are curves of swimming styles with greater resistive forces. Furthermore, the absolute value of P_{max} is an indication of the propulsive force generated. Differences in the propulsive force can be determined by comparing the P_{max} values of individuals completing both swimming styles. In special circumstances propulsive forces from different swimming style can also be compared using velocities standardized to known levels of performance. For example, the International Point System assigns points to competition times based upon the relation of those times to a historical statistical analysis of the best times in each event. Therefore a swimmer of who has achieved a set point standard in one swimming style can be matched for comparison with a different swimmer who has achieved the same point standard in a different swimming style.

Differences and changes in both propulsive and resistive forces should be interpretable using a graph of P_{max} vs. v_{max}. Should a swimmer experience more resistive force, the curve should shift to the left indicating a greater P_{max} requirement for the same v_{max} (See Figure 11). Similarly a decrease in resistance should cause the curve to shift to the right. Changes in propulsive forces should result in movement along the characteristic P_{max} vs. v_{max} curve of the swimming style without deviation from the curve (See Figure 12). If propulsive force increases, then the point of the individual should slide upwards and to the right along the curve. If propulsive force decreases, then the point of the individual should slide downwards and to the left along the curve. Statistically it is necessary to first determine the most appropriate function to fit the curve. After this has been done, the curve can be linearized for use with ANCOVA with v_{max} as the covariate. The MPM hypothesizes that changes in resistive forces will produce significant differences in the linearized P_{max} between the two styles when analyzed by ANCOVA with v_{max} as the covariate. In contrast, changes in propulsive forces should show significant differences in P_{max} between the two styles when analyzed by ANOVA, but not when analyzed by ANCOVA.

Figure 11

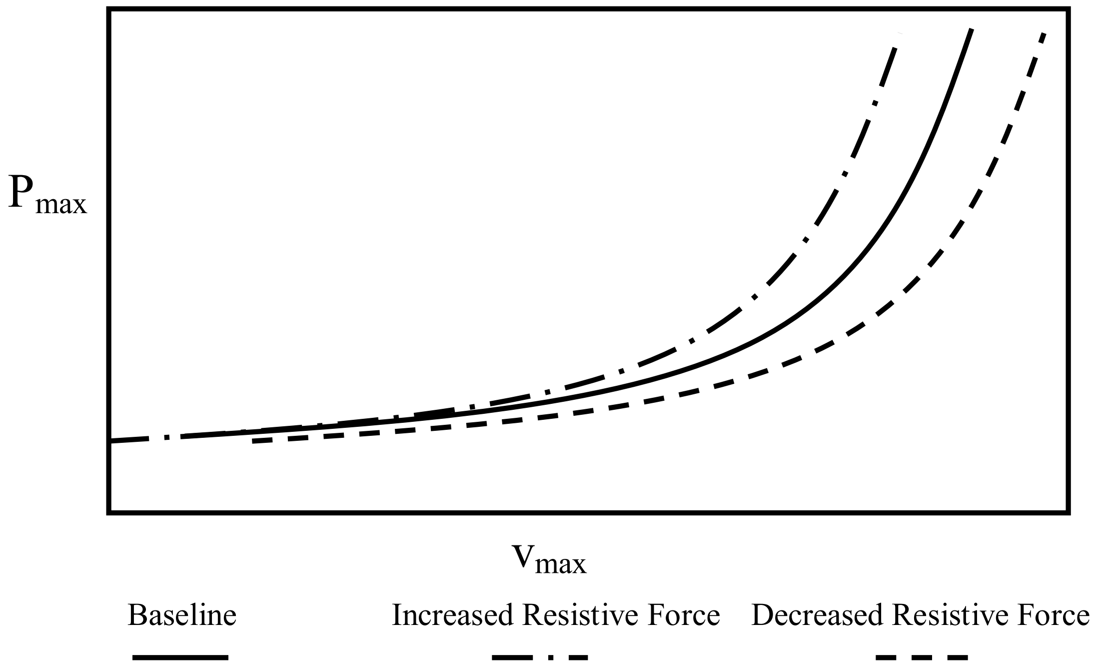


FIGURE 1 – The MPM predicted effect of change in resistive force as seen on the P_{max} vs. v_{max} graph

Figure 12

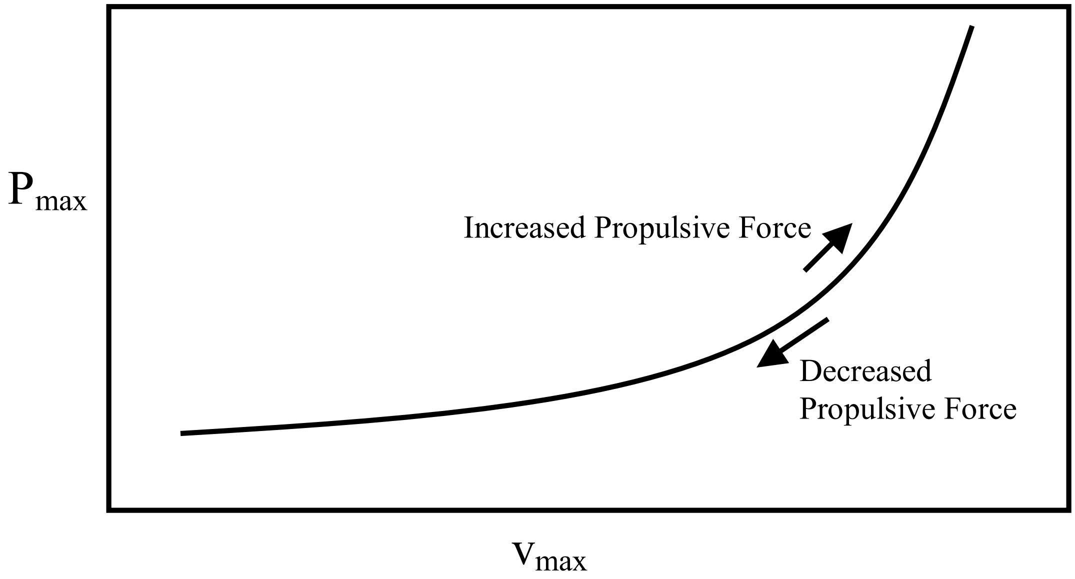


FIGURE 12 – The MPM predicted effect of change in propulsive force as seen on the P_{max} vs. v_{max} graph

Conclusion

Beginning with the link of fully-tethered swimming force (F_{max}) to propulsive forces, moving through the connections between semi-tethered swimming and the propulsive and resistive forces experienced during swimming, and finishing with the relationship between P_{max} and v_{max}; the face validity of the Max Power Model for the quantitative evaluation of resistive and propulsive forces during swimming has been established. While not without its own limitations, the MPM is widely adaptable and has the ability to distinguish between changes in resistive and propulsive forces. Perhaps the greatest strength of the MPM is its accessibility and lack of expensive specialized equipment. The proposed study will evaluate the validity of the MPM in situations of a known change in resistive and propulsive force and will compare the results of the MPM with the Velocity Perturbation Model.

Velocity Perturbation Model

Introduction

The Velocity Perturbation Model was first used by Kolmogorov and Duplishcheva in 1992. Since that time, the model has been used to calculate resistive forces during maximal effort swimming for over 950 swimmers in 7 published works. The assumptions of the VPM have been tested and the results have been compared to other methods of determining resistive forces. For these reasons, the VPM is perhaps the gold standard of resistive force determination using assisted or resisted swimming. Discussion of the literature pertaining to the VPM will begin with a description of the methodology, evaluation of the assumptions, and tests of the validity. The review will continue with an analysis of the resistive force results for the VPM including the relationship to maximum velocity and attempts to manipulate the results with known changes.

Methodology

As described by Kolmogorov and Duplishcheva (1992), the testing procedure for the VPM consists of two maximal effort 50 m swims. The first trial is a free swim and establishes v_{max}. The second trial is swum against a resistance, in this case provided by a towed device. The towed device is referred to by the authors as a boat and has been calibrated for resistive force over the range of velocities used in the study. Several boats were designed and calibrated for use with swimmers of different abilities. The goal in the choice of boat was to decrease the velocity of the swimmer by 10% for the second trial.

The boat was towed approximately 3.5-4.5 times the height of the swimmer behind the swimmer in order to minimize the random effects of turbulence created by the swimmer on the load force provided by the boat. Determination of the tether distance was completed by repeatedly towing a small number of subjects in a passive state with the boat attached. The tether distance was gradually increased until the velocity did not change between repeated trials.

During the swim, the 30 m between the 15th and 45th m was timed and the velocity of each swim was calculated. The authors mention that the time was measured using an electronic system and that this decreased the error in timing from 0.8% with a hand time to 0.1%. The authors do not describe how electronic timing was accomplished, nor do they cite a source or data verifying the purported increase in accuracy.

Calculation of the resistive force requires the force of the load as well as the velocity of both the free swimming and tethered trials. The calculation is based upon the assumption that the useful propulsive power output (P_{prop}) of each of the two trials is equal. During all swimming some of the power or energy imparted to the water by the swimmer (P_{total}) does not propel the swimmer forward (P_{prop}), but instead increases the kinetic energy of the water (P_{kin}). This can be thought of as a form of inefficiency. It is possible that the proportion of power that produces useful propulsion and the proportion which gives the water kinetic energy changes with the F_{load} of the tether, but this change has not been quantified. Furthermore, because the water under the swimmer is moving more slowly it is likely based upon previously presented theory that P_{total} increased with F_{load}. Thus the assumption of equal P_{prop} is relies upon one of two conditions. The assumption of equal P_{prop} can be met if the change in P_{total} is insignificant and the ratio between P_{kin} and P_{prop} does not change with tethering. The assumption of equal P_{prop} can also be met if P_{total} increases, but the ratio of P_{kin} to P_{prop} also increases proportionally. Evaluation of this assumption is presented in the next section. Making the assumption of equal P_{prop}, the formula used by Kolmogorov and Duplishcheva (1992) to calculate F_{res} can be derived.

Derivation 3

The authors start by calculating the useful propulsive power output for each of the two swimming conditions:

$P_{prop1} = F_{res1} * v_1$

$P_{prop2} = F_{res2} * v_2 + F_{load} * v_2$

Where F_{load} is the force exerted on the swimmer by the boat

The second assumption made is that F_{res} is proportional to the square of velocity:

$F_{res1} = Av_1^2$ (A is a constant often called the drag coefficient) and $F_{res2} = Av_2^2$

Therefore

$P_{prop1} = Av_1^2 * v_1 = Av_1^3$

$P_{prop2} = Av_2^2 * v_2 + F_{load} * v_2 = Av_2^3 + F_{load} * v_2$

Assuming the P_{prop} is constant at maximal effort regardless of water velocity conditions:

$P_{prop1} = P_{prop2}$

Therefore

$Av_1^3 = Av_2^3 + F_{load} * v_2$

Since F_{load}, v_1, and v_2 are measured A can be determined from an algebraic manipulation of the above formula:

$A = F_{load}*v_2/(v_1^3 - v_2^3)$

Finally, the resistive forces in the unloaded situation can be calculated by substituting back in for the constant:

Equation 4

$F_{res1} = (F_{load}*v_2/(v_1^3 - v_2^3))v_1^2$

Recall that F_{res1} is a measure of the F_{res} at v_{max}.

Kolmogorov and Duplishcheva also calculate what they use as the drag coefficient which is known as C_x. C_x can be defined in terms of A.

$A = \frac{1}{2}C_x\rho S$ or $C_x = 2A/\rho S = (2/\rho S)*F_{load}*v_2/(v_1^3 - v_2^3)$

Where ρ is the density of water and S is a characteristic surface area of the swimmer (in other words it is the cross sectional area of the swimmer). This formula was derived for simple shapes moving passively through the water. The application of this formula to a swimmer in motion is questionable and introduces another possible source of error into the calculation. For this reason the term C_x will not be used in this discussion. Any comparisons made will focus on the more general drag coefficient (A).

Assumptions

As seen in the previous section, two assumptions are made in order to calculate F_{res} using the VPM: equal power output and the proportionality of F_{res} to v^2. The first assumption is identified by the authors, the second is not. The equal propulsive power assumption has also been tested by a number of other researchers in a wide variety of ways with a variety of conclusions. The assumption of proportionality to v^2 has received limited testing as the measurement requires an accurate measurement of F_{res}.

Equal Propulsive Power Assumption

In addition to identifying the equal propulsive power assumption, Kolmogorov and Duplishcheva (1992) attempt to examine the validity of the assumption. In order to do so, 20 front crawl swimmers were tested with two different configurations of the boat and thus presumably two different values for F_{load}. The average F_{load} value in each for the different configurations of the boat was not reported, highlighting the difficulty in using a velocity dependent source for F_{load}. The assumption that the boat configuration with the larger F_{load} at each velocity causes the largest F_{load} for the test is undermined since the swimmer will have a smaller velocity with this configuration. Because the authors are using the different boat configuration to test the effect of different values for F_{load} and the authors know the value for F_{load} in each case, it can be assumed that the F_{load} values are indeed different, but the direction and magnitude of those differences were not reported. The resulting values for F_{res} were 50.21 ± 2.65 N and 50.99 ± 2.94 N for the larger and smaller resistance boat configurations respectively. No statistical comparison was presented to verify similarity.

Kugovnik, Bednarik, Strumbelj, and Kapus (1998) more rigorously explored the idea of testing the equal propulsive power assumption by comparing F_{res} calculated using different values of F_{load}. Seventeen highly trained male swimmers (age > 16 yrs, mass = 74.3 ± 7 kg, height 180.6 ± 4.7 cm) completed maximal effort 18 m swims with no load ($v_{max} = 1.71 \pm 0.84$ m/s) and under 4 different boat configurations. F_{load} was measured during each trial by a force transducer placed in the tether between the boat and the swimmer. In order to measure the velocity of the swim, the subject was attached via a cable to a potentiometer. As the swimmer moved away from the potentiometer, the electrical resistance of the potentiometer changed. The voltage drop across the potentiometer was recorded with time reference onto a computer which calculated velocity beginning 2.5 m from the wall. F_{res} was calculated using each of the 4 loaded trials in comparison with the free swimming trial (Table 9). Also included in Table 9 are the average values of F_{load} for each boat configuration.

Table 9

Boat Configuration	F_{load} (N)	F_{res} (N) at v_{max}
1	9.70 ± 0.99	76.37 ± 27.19
2	12.47 ± 1.13	70.75 ± 37.15
3	13.12 ± 0.92	75.03 ± 25.74
4	37.62 ± 4.9	64.94 ± 37.51

TABLE 9 - The average and standard deviation of the F_{load} of each boat configuration and the F_{res} calculated using the VPM with that boat configuration by Kugovnik et al. (1999)

In analyzing the differences between F_{res} calculated using different boat configurations, Kugovnik et al. (1998) ran a series of paired t-tests ($\alpha = 0.05$) and found no significant differences. Thus the conclusion was reached that F_{load} did not effect F_{res} and the equal propulsive power assumption is valid. However, a t-test is not a test of similarity but of difference. Finding no significant difference with an $\alpha = 0.05$ indicates that there is more than a 5% chance that numbers come from the same distribution. This finding can only be used to conclude that there is less than a 95% chance the numbers are from different distributions and is not rigorous or at all conservative. Without the proper statistical analysis no conclusions can be drawn from the data. That is not to say that the data is without implication. Boat configurations 2 and 3 have very similar values for F_{load} and demonstrate almost as much difference in F_{res} as is seen between configurations 1 and 2. This may be an indication that regardless of the validity of the equal propulsive power assumption, the error introduced by this assumption into the calculation of F_{res} is less than the random error inherent in the measurement. With the random error, a trend does not appear until the largest of the loads. While the authors state that no trial deviated by more than 15% from v_{max}, the trials with boat configuration averaged 1.41 ± 0.10 m/s which is an average of 17.8% lower than v_{max}. This deviation is far greater than the intended 10% as outlined in the methodology of Kolmogorov and Duplishcheva (1992) and undermines the applicability of the trend. The implication that random error overwhelms the error due to the assumption of equal power is perhaps the most prevalent trend in the data of Kugovnik et al.

Strojnik, Bednarik, and Strumbelj (1999) took the idea of comparing F_{res} using different loads a step further by deriving a formula to calculate F_{res} from two loaded swims using the equal propulsive power assumption. The derivation is very similar to the original of Kolmogorov and Duplishcheva (1992) however instead of beginning with $P_{prop1} = F_{res1}*v_1$, the calculation begins with $P_{prop1} = F_{res1}*v_1 + F_{load1}*v_1$ as seen in Derivation 4.

Derivation 4

$P_{prop1} = F_{res1}*v_1 + F_{load1}*v_1$

$P_{prop2} = F_{res2}*v_2 + F_{load2}*v_2$

Assuming that F_{res} in both cases is proportional to the square of velocity,

$F_{res1} = Av_1^2$ (A is a constant) and $F_{res2} = Av_2^2$

Therefore

$P_{prop1} = Av_1^2*v_1 + F_{load1}*v_1 = Av_1^3 + F_{load1}*v_1$

$P_{prop2} = Av_2^2*v_2 + F_{load2}*v_2 = Av_2^3 + F_{load2}*v_2$

Assuming the P_{prop} is constant at maximal effort regardless of water velocity conditions:

$P_{prop1} = P_{prop2}$

Therefore

$Av_1^3 + F_{load1}*v_1 = Av_2^3 + F_{load2}*v_2$

Since $F_{load1,}$ F_{load2} , v_1, and v_2 are measured A can be determined from an algebraic manipulation of the above formula:

$A = (F_{load2}*v_2 – F_{load1}*v_1)/(v_1^3- v_2^3)$

Finally, the resistive forces in the unloaded situation can be calculated by substituting back in for the constant:

Equation 5

$F_{res1} = (F_{load2}*v_2 – F_{load1}*v_1)*v_1^2/(v_1^3- v_2^3)$

Strojnik, Bednarik, and Strumbelj (1999) tested 5 male junior swimmers of a Slovenian “national level” (age = 15-18 years, mass = 67-84 kg, height = 176-195 cm). Numerical results are not presented and the graphical presentation for the equal propulsive power assumption includes data from only one of the 5 subjects. While the authors conclude that the equal propulsive power assumption does not hold, this evaluation lacks credibility. The authors seem to confuse P_{load} and P_{prop} a number of times throughout the article which poisons their conclusions.

The authors also examine the effect of unequal powers on the calculated values for F_{res}. The derivation for the unequal propulsive power assumption deviates from the assumption of equal power by inserting a coefficient representing the ratio of the two powers (k).

Derivation 5

Beginning at one step before the deviation from derivation 4:

$P_{prop1} = Av_1^2 * v_1 + F_{load1} * v_1 = Av_1^3 + F_{load1} * v_1$

$P_{prop2} = Av_2^2 * v_2 + F_{load2} * v_2 = Av_2^3 + F_{load2} * v_2$

Assuming P_{prop} is not constant:

$P_{prop1} = kP_{prop2}$

Therefore

$Av_1^3 + F_{load1} * v_1 = k(Av_2^3 + F_{load2} * v_2)$

Solving the above equation for A:

$A = (kF_{load2} * v_2 - F_{load1} * v_1)/(v_1^3 - kv_2^3)$

Substituting in for A to solve for F_{res}:

Equation 6

$F_{res1} = (kF_{load2} * v_2 - F_{load1} * v_1) * v_1^2/(v_1^3 - kv_2^3)$

As the value for k is unknown, Equation 6 can not be used to solve directly for F_{res1}. However Strojnik, Bednarik, and Strumbelj (1999) use Equation 6 to estimate the effect of different ratios between the powers (values of k) on the calculated for F_{res1} for a single subject (Table 10). The results show that the error induced in the measurement of F_{res} for the VPM is great should the equal propulsive power assumption not hold.

Table 10

Ratio of Powers (k)	1	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.1
F_{res} (N)	57.9	61.7	65.9	70.6	75.8	81.7	88.4	95.9	104.6	114.7	126

TABLE 10 - The sensitivity of F_{res} calculated by the VPM to violation of th equal power assumption demonstrated using a ratio of powers by Strojnik, Bednarik, & Strumbelj (1999)

Thorp and Wilson (2003) set about testing the equal propulsive power assumption from another angle. Equating metabolic power with mechanical power, six experienced male swimmers between the ages of 20 and 29 years were tested for oxygen consumption under three conditions in a flume. The first condition was a submaximal swim. The second was a submaximal swim at 10% lower velocity against an external resistance provided by a weight and pulley system during with the swimmer was instructed to swim with the same effort. The method by which F_{load} was set was not reported. The third was a swim that was 10% slower than the original but with no external resistance. The authors found no significant difference between the oxygen consumption in the first and second conditions (3060 ± 350 ml/min and 3170 ± 380 ml/min respectively). While this would logically lead to the conclusion that it is possible for a tethered swim at 10% lower velocity to require the same metabolic rate as a free swim, it does not support the conclusion that this will always be true. Modification of the load would indubitably change the oxygen consumption of the subjects swimming at 10% lower velocity. Furthermore, no evidence is presented to suggest that metabolic power is proportional to P_{prop}. In fact, one of the sources of concern for the equal propulsive power assumption is a change in the ratio of P_{kin} to P_{prop} between tethered and untethered swimming which would uncouple P_{prop} from P_{total} and therefore metabolic power output. Based on these two concerns, the authors statement that, “the equal power output assumption that is integral to the measurement of active drag [F_{res}] using the additional hydrodynamic body method [Kolmogorov and Duplishcheva (1992)] can be assumed to be acceptable for submaximal swimming efforts where the submaximal swim velocities are well controlled as in flume swimming” is not supported by the data presented.

The final test of the equal propulsive power assumption was made using the MAD system in conjunction with the VPM in a cooperative effort by Toussaint, Roos, and Kolmogorov (2004). Each of six top-level international competitive swimmers (female N = 1, age = 19 yrs, mass = 62 kg, height = 1.75 m, 100 m time = 55.1 s, male N = 5, age = 21 ± 4 yrs, mass = 75.2 ± 4.5 kg, height = 1.90 ± 0.08 m, 100 m time = 51.32 ± 1.64 s completed MAD testing and between 1 to 3 trials using the methodology of the VPM. As will be described later, the MAD system can be used to determine a well fit relationship between velocity and F_{res} for each individual. This relationship was used to predict F_{res} during the free swimming and the loaded trial of the VPM. From these predictions, P_{prop} was calculated for both conditions of the VPM. The difference between these P_{prop} during free swimming (111 ± 25 W) and P_{prop} during loaded swimming (97.3 ± 23 W) was an average of 13.2 ± 16.4 W or 11.2 ± 12.7% of the free swimming power. As can be seen by the large standard deviation, the difference between powers varied widely between trials. Toussaint, Roos, and Kolmogorov related this difference to the difference between the calculated values for F_{res} during maximal free swimming of the MAD and VPM. A linear correlation of R = 0.94 between ΔF_{res} and ΔP_{prop} was noted. Thus it can be seen that based upon calculations of P_{prop} using the MAD system, the difference between the P_{prop} of the two different trials of the VPM accounted for 88% of the variability seen in the differences between the F_{res} calculated using the MAD and the VPM. As the intercept of the line of best fit was not significantly different from the origin, the authors suggest that violation of the equal propulsive power assumption accounts for the differences in the values measured. While this interpretation is correct, it is specific to each trial and runs the risk of evaluating the error inherent in the measurement and not the underlying assumption. The large standard deviation of the difference of powers in the group data suggests that the underlying assumption of equal power is not necessarily ruled out. As the raw data is provided simple statistics can be run to evaluate this more thoroughly. Of the six subjects, three completed three trials, one completed two trials, and the remaining two subjects completed only one trial. Using all thirteen trials, a paired t-test of the P_{prop} between the free swimming and loaded trials shows a significant difference between the two ($p = 0.015$). A paired t-test is not wholly appropriate as there are multiple trials by the same subject. A two-way repeated ANOVA for P_{prop} with trial number and loaded/free swimming as the independent variables is run for the three subjects who completed all three trials. The statistical power suffers due to the low subject number, but the results reveal no interaction, no significant main effect for loaded vs. free swimming, and a significant main effect for trial number ($p < 0.05$). Thus the two analyses imply contradicting conclusions with the first suggesting that the P_{prop}'s are indeed different between the free swimming and loaded conditions and the second suggesting that the effect of the load is not significant and is less important than the trial number (perhaps symptomatic of a learning effect).

Toussaint, Roos, and Kolmogorov (2004) also theoretically determined the effect of P_{prop} differences on the calculated values of F_{res} using the VPM. Similar to the sensitivity tests of Strojnik, Bednarik, and Strumbelj (1999), Toussaint et al. conclude that F_{res} is highly sensitive to deviations in the P_{prop} between the two tests with a 15% difference in P_{prop} leading to a 30% difference in F_{res}. Toussaint et al. compared the experimental data of ΔF_{res} and ΔP_{prop} to the theoretical predictions graphically and found good qualitative agreement.

From the literature pertaining to the equal propulsive power assumption of the VPM few conclusions can be reached. Evidence both in support of and contrary to the equal propulsive power assumption lacks credibility or does not distinguish between the concept of equal power output and the error inherent in each test. The only conclusions that may be drawn are that the VPM calculation for F_{res} is highly sensitive to variations in P_{prop} between the free and loaded conditions and that regardless of whether the assumption holds on a conceptual level, experimental error dwarfs the presence of a systematic difference between P_{prop} in the loaded and free swimming conditions of the VPM.

Assumption of F_{res} α v^2

While the assumption of equal power output has been tested in a variety of ways, the second assumption can only be assessed by the results of studies which have attempt to measure the relationship between velocity and F_{res} during swimming. Just as the sensitivity of the VPM to violation of the equal propulsive power assumption could be theoretically determined, so can the sensitivity of the assumption of F_{res} α v^2.

While the MAD system is the primary and most valid methodology to determine the relationship between F_{res} and velocity, other methodologies have also reported values using a power fit. While the exponent of velocity is usually close to 2, the majority of authors report exponents slightly greater than two. This trend is particularly true of the MAD system which typically reports that F_{res} proportional to approximately velocity raised to the 2.2 or 2.3 power. As this relationship is not agreed upon, evaluation of the assumption of $F_{res} \alpha v^2$ is more appropriately assessed using the sensitivity of the calculation of F_{res} to violation of this assumption.

Toussaint, Ross, and Kolmogorov (2004) evaluated the effect of violation of the $F_{res} \alpha v^2$ assumption on the values for F_{res} obtained from the VPM. The group mean of n (2.34) calculated from the MAD data of this particular group of subjects was used as the correct value and in this circumstance the assumption of $n = 2$ lead to 10% error in F_{res}. Comparison to the broader context of the entire range of reported values for n leads the authors to conclude that the assumption of $F_{res} \alpha v^2$ leads to little error in comparison to other sources.

Tests of validity

The validity of the measurement of F_{res} using the VPM has been tested in two ways: reproduction of F_{res} values under both free and tethered condition and comparison with values from the MAD system. Kolmogorov and Duplishcheva (1992) offer what they term "verification of the method" for VPM. Kolmogorov and Duplishcheva verify that equal P_{prop}s produce equivalent values of F_{res} from both the free swimming and load bearing conditions. As they are unable to quantify the total power output during swimming, they use a passive condition in which the force on the swimmer is applied by an external source. Ten swimmers were passively towed using a weight and pulley system with the weight adjusted to cause each swimmer to move at approximately his free swimming velocity. The propulsive power was calculated from the product of the velocity, the mass of the weight, and the acceleration due to gravity. The swimmer was then attached to the boat and was once again passively towed with the weight and pulley system. In this case the weight was adjusted to achieve a power equal to that of the trial without the boat. As could be expected in the second trial, the mass was larger and the velocity smaller than in the first. Using the velocities of the two trials and the F_{load} of the boat, Equation 4 was used to calculate F_{res} for both the loaded and unloaded trials. The authors suggest that this comparison gives "an indication of the error made in the determination of drag [F_{res}]". They found a difference of only 1% between the two calculations ($F_{res1} = 73.25 \pm 4.20$ and $F_{res2} = 74.16 \pm 4.22$ N). The logic behind this comparison is flawed. Kolmogorov and Duplishcheva explicitly state that the velocity of the second trial was less than the velocity of the first trial. As the dependence of F_{res} on v^2 is an assumption of the derivation and v_1 is not equal to v_2, F_{res1} should not be equal to F_{res2}. Thus the inability to distinguish between F_{res1} and F_{res2} is either an indication that the difference between v_1 and v_2 is small or that the error in the method is large.

In addition to testing both of the assumptions inherent in the VPM Toussaint, Roos, and Kolmogorov (2004) also directly compared the values of F_{res} obtained from the MAD system and the VPM. Using the same subjects and trials as cited in preceding sections, the authors found a significant difference between F_{res} for the VPM and the MAD system using a t-test ($p = 0.029$). The analysis of these values using a t-test is flawed as some of the subjects are completing multiple tests. However, the finding of a difference using a t-test is very conservative in terms of ruling out similarity. Further analysis of the raw data presented in the article shows that the correlation between the F_{res} values of the two tests is not significant ($R = 0.22$, $p > 0.05$). While the values from the tests are different, these differences can be accounted for by the individual deviations from the equal propulsive power assumption as described in the previous section. This leads the authors to conclude that the VPM and the MAD system “measure essentially the same phenomenon.”

While the assumptions of the VPM have been tested by a number of authors, establishment of the validity of the measure beyond face validity is limited. The proposed study will aim to provide more evidence by which the validity of the VPM can be evaluated.

Results

Four articles list values of F_{res} at v_{max} as determined by the VPM. Of those four, three are authored in some capacity by the lead author of the original article. Unlike many of the other swimming topics covered, data for strokes other than front crawl is plentiful. The majority of the data comes from the original article defining the VPM and a follow up that expands the range of subject abilities in addition to the subject number. The primary focus of the two other sources was to examine the assumptions and validity of the VPM.

In the initial description of the VPM Kolmogorov and Duplishcheva (1992) tested male and female members of the soviet national team training for the Goodwill Games in their specialty stroke. The average and standard deviation of F_{res} for each stroke and sex pair are listed in Table 11 along with descriptive anthropometrics from each group.

Using the individual data presented in the article, an ANCOVA for F_{res} with sex and stroke as the independent variables and v_{max}^2 as the covariate (as assumed by the VPM) reveals no significant interaction between sex and stroke and no significant main effect for sex. Stroke is a significant main effect ($p < 0.05$) and comparisons on means at $v_{max}^2 = 2.3829$, $v_{max} = 1.54$, (presented in Table 12) made with a Bonferroni adjustment show significant differences between breaststroke and all of the other strokes and no other differences. The differences seen between the strokes follow the same pattern as those seen in F_{max} and P_{max} when standardized for $v_{max.}$ Breaststroke has the largest F_{res} followed by butterfly and backstroke which are very close together and finally front crawl which is the smallest.

Table 11

Stroke	Sex	N	Age (yrs)	Mass (kg)	Height (cm)	v_{max} (ms^{-1})	F_{res} (N)
Free	F	10	16.3 ± 1.8	63.4 ± 4.1	175.0 ± 3.5	1.61 ± 0.05	53.17 ± 11.70
Free	M	14	20.2 ± 1.8	79.3 ± 5.2	186.4 ± 5.2	1.77 ± 0.10	85.36 ± 38.74
Fly	F	10	19.0 ± 2.6	63.8 ± 4.6	176.0 ± 4.5	1.50 ± 0.05	53.33 ± 12.60
Fly	M	13	19.4 ± 1.6	78.5 ± 3.8	184.7 ± 4.6	1.67 ± 0.11	96.63 ± 29.23
Back	F	10	16.8 ± 1.5	63.9 ± 3.5	173.7 ± 3.9	1.38 ± 0.03	44.54 ± 8.52
Back	M	10	19.6 ± 3.1	78.1 ± 4.1	186.1 ± 5.3	1.56 ± 0.12	77.63 ± 32.45
Breast	F	10	16.8 ± 1.0	64.0 ± 5.8	177.4 ± 3.1	1.28 ± 0.04	68.22 ± 15.77
Breast	M	12	20.3 ± 2.3	79.8 ± 6.1	184.3 ± 4.0	1.39 ± 0.09	88.84 ± 36.30

TABLE 11 - Average and standard deviation divided by stroke and sex for population describing measures, v_{max}, and F_{res} at v_{max} as calculated using the VPM from Kolmogorov & Duplishcheva (1992)

Table 12

Stroke	F_{res} (N)		
Butterfly	69.154	±	5.491*
Backstroke	69.253	±	6.005*
Breaststroke	102.772	±	8.351
Front Crawl	49.575	±	7.344*

* significantly different from breaststroke ($p < 0.05$)

TABLE 13 - Adjusted means (at $v_{max}^2 = 2.383$) collapsed across sex from an ANCOVA for F_{res} of the VPM with stroke and sex with v_{max}^2 as the covariate. Data from Kolmogorov and Duplishcheva (1992)

Following up on the initial study Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997) report results for VPM testing of 310 females and 487 males with an age range of 10-28 years and a wide range of ability as indicated by v_{max} (descriptive anthropometrics were not provided). The results were presented in graphical form as seen in Figure 13 for females and Figure 14 for males. In order to determine approximate values for each point the graphs were digitized. The values for $v_{max} = 1.55$ m/s can be used for comparison with the previous study and Table 12. As the number of subjects represented by each point on the graph is not known, males and females can not be combined in an average and must be compared separately. F_{res} at 1.55 m/s from each study is compared in Table 13. Values are missing from Table 13 if none of the subjects attained the desired v_{max}. The values that are present are in relatively good agreement between the two studies. The F_{res} for male breaststrokers at $v_{max} = 1.35$ m/s and 1.45 m/s were 68.2 N and 93.3 N respectively allowing for the prediction that were values for 1.55 m/s available, they would also be in agreement.

Table 13

		F_{res} (N)			
Author	Sex	Butterfly	Backstroke	Breaststroke	Freestyle
Kolmogorov and Duplishcheva (1992)	Mix	69.2	69.3	102.8	49.6
Kolmogorov et al. (1997)	Male	69.2	65.8		44.0
Kolmogorov et al. (1997)	Fem	51.5			41.0

TABLE 13 - Comparison of F_{res} (computed using the VPM) between the ANCOVA adjusted means at v_{max} = 1.54 ms^{-1} from Kolmogorov and Duplishcheva (1992) and the means for v_{max} = 1.55 ms^{-1} from Kolmogorov et al. (1997)

The final two studies that present values are those of Toussaint, Roos, and Kolmogorov (2004) and Kugovnik, Bednarik, Strumbelj, and Kapus (1998). Both of these studies were done to examine the validity and the assumptions of the VPM, have relatively low subject numbers, and used only front crawl. Descriptions of the methodologies and subjects for each of these studies was given in the section on assumptions. The results of the studies are compared with v_{max} matched averages from Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997) in Table 14. The presented results for Kugovnic et al. are those of the third boat configuration for which the velocity perturbation most closely matched the 10% designated by the original methodology. The results from all three studies show good agreement.

Table 14

Author	v_{max} (ms^{-1})	F_{res} (N) at v_{max}
Toussaint	1.64 ± 0.10	53.18 ± 18.76
Kolmogorov (1997) Males	1.65	52.1
Kolmogorov (1997) Females	1.65	48.1
Kugovnik	1.71 ± 0.84	75.03 ± 25.74
Kolmogorov (1997) Males	1.75	77.5
Kolmogorov (1997) Females	1.75	61.6

TABLE 14 - Agreement between three studies (Kolmogorov et al., 1997; Kugovnik et al., 1998; Toussaint, Roos, & Kolmogorov 2004) using the VPM to calculate F_{res} at v_{max}

In conclusion, results of the four studies listing F_{res} values as calculated using the VPM show good agreement when the v_{max} of the subject is taken into account. The relationships between the F_{res} of the four competitive strokes as determined by the VPM are similar to those seen for both F_{max} and P_{max}.

Relationship to v_{max}

No methodology has addressed the link between F_{res} at v_{max} and v_{max} to the extent of the VPM. Establishing this link requires a large amount of testing and thus the ease of completion and low cost of the VPM make it an appropriate methodology for this assessment. The evidence for the relationship between F_{res} and v_{max} from the VPM has been determined using a large number of subjects in two sources. The graphical results of Kolmogorov, Rumyanstseva, Gordon, and Cappaert (1997) are presented with minor modifications in Figures 13 and 14. Using the means at each velocity, a function can be fit. Combining the means of the males and females and using a power function, the fit for each of the strokes is greater than $R = 0.97$. There is a noticeable deviation from the curve fit at the highest velocities of the males in each stroke. The authors speculate that the subjects capable of reaching these high v_{max}'s can only do so because they are more efficient and therefore have lower values of F_{res} relative to velocity than the average swimmer.

Figure 13

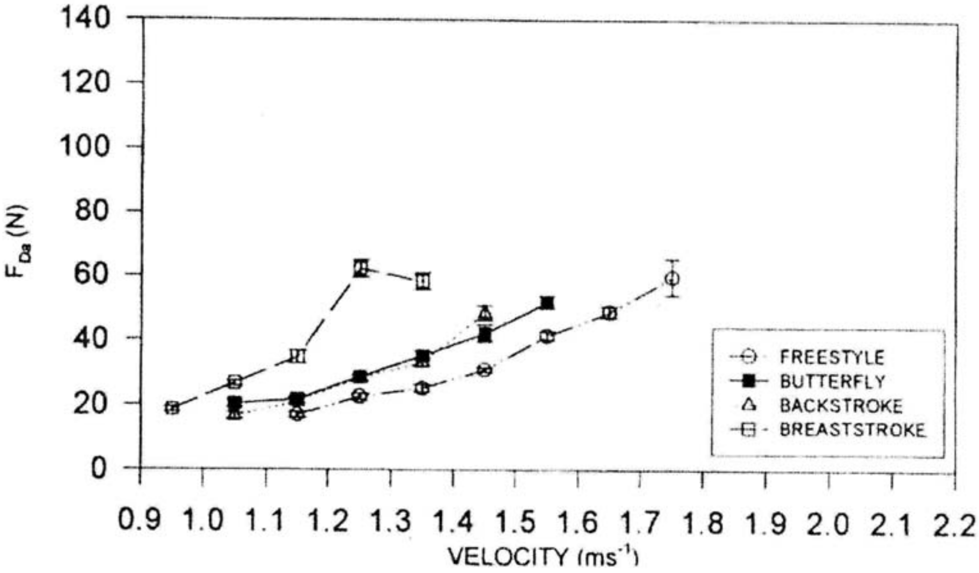


FIGURE 13 – Resistive force (F_{ad}) plotted vs. v_{max} (velocity) for females from Kolmogorov, Rumyanstseva, Gordon, and Cappaert (1997)

Figure 14

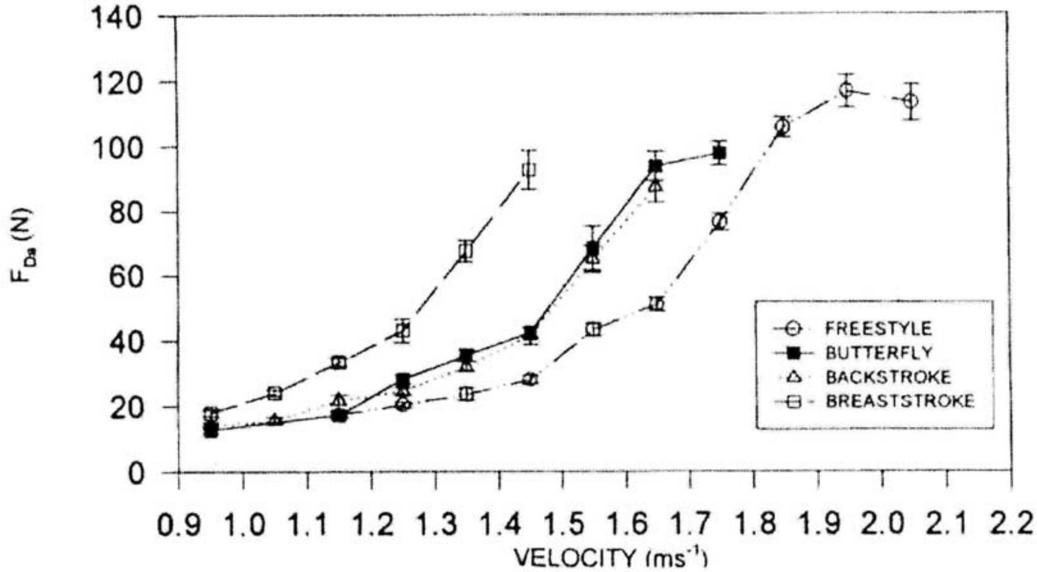


FIGURE 13 – Resistive force (F_{ad}) plotted vs. v_{max} (velocity) for males from Kolmogorov, Rumyanstseva, Gordon, and Cappaert (1997)

Fomitchenko (1999) determined F_{res} using the VPM for a group of 56 male swimmers during front crawl. The group was divided into 3 subgroups by age, with the average age of the three groups being 11.5 (N = 23), 13.8 (N = 23), and 17.4 (N = 10) years. Linear correlations between F_{res} and v_{max} were determined for each subgroup. For both the 11.5 and the 13.8 year old subgroups the correlation was not significant (R = 0.27 and R = 0.23 respectively). In contrast for the 17.4 year old age group, the linear correlation between F_{res} and v_{max} was both significant and large R = 0.95. The difference in correlative values is striking and is unrelated to the variance in ability level within each group as the standard deviation of v_{max} in the oldest group is the lowest of any of the three groups. Assuming that the relationship of F_{res} to v_{max} is adequately described by the data of Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997), the most plausible explanation of the change in correlations between the age groups is the placement of the three groups on the curve. The 11.5 and 13.8 year old groups, with $v_{max} = 1.36 \pm 0.04$ and 1.46 ± 0.133 m/s respectively, lie on the flat portion of the curve causing variation in F_{res} to be small and the linear correlations to be small. The 17.4 year old group lies on the steep portion of the graph with large variability in F_{res} and results in a large correlation.

Correlative values can also be calculated for the two studies in which raw data is presented. The raw data from Kolmogorov and Duplishcheva (1992) yields significant power correlations between F_{res} and v_{max} of $R = 0.57$, 0.73, 0.51, and 0.73 for butterfly, backstroke, breaststroke, and front crawl respectively. The raw data from Toussaint, Roos, and Kolmogorov (2004) shows both non-significant linear and power correlations of $R = 0.04$ between F_{res} and v_{max}. The poor fit of this graph can not be explained by either the position on the curve or the variability in the data as $v_{max} = 1.64 \pm 0.10$ m/s.

When considered as a group, the correlations using individual data are widely varied and tend to be low. In contrast the power fits made using the group data of Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997) show extremely high correlations. While the use of group means will inflate the correlation to a certain extent, the large difference between the correlations using group and individual data indicates that the underlying relationship between F_{res} and v_{max} is strong, but the random error in the measurements is large.

Manipulations

One of the concepts of the proposed study is to manipulate the conditions of swimming in a known or unknown way and examine the reaction of the methodology.

Bideau, Colober, Nicolas, Le Guerroue, Multon, and Delamarche (2003) utilized this concept when they measured the F_{res} of elite French fin swimmers. The four subjects showed values of F_{res} between 77 and 103.5 N. Comparison with other values is difficult as the v_{max} for each subject is not listed, but these values are in the same range as those of other sources. As the purpose of the article is focused on establishing the use of the specific testing equipment for the VPM, the value of the manipulation of the swimming condition is lost in the reporting of the results, but a precedent for manipulation has been set.

Conclusion

The VPM is the most widely used and well developed method of determining F_{res} using assisted or resisted swimming. In this position, the validity and assumptions of the VPM have been examined by a number of methods. The VPM has also be used to define the relationship between F_{res} at v_{max} and v_{max} in a more extensive way than any other methodology. The evaluation of both the assumptions and the relationship between F_{res} and v_{max} are undermined by the large amount of random error in the testing procedure. While the underlying relationships and assumptions may be correct, as can be seen using group means, the large variation in individual data leads many authors to the conclusion that the relationships do not exist or the assumptions have been violated. One contributor to the random error is the use of a velocity dependent “boat” as the source of resistance. Thus despite being the most scrutinized ARS method, the VPM requires further investigation to place the results in the appropriate context.

Other Methods for Determining Resistive and Propulsive Forces in Swimming

Introduction

This section will provide a brief review of the methods besides the VPM and the MPM that have been used to evaluate resistive and propulsive forces during swimming. Rather than results, this section will focus on the appropriate use of each of the methodologies. Each subsection will present the methodology, the work that has been completed using this methodology, and finally the relative strengths and weaknesses of the methodology.

Other Methods Using Assisted and Resisted Swimming

The methods of measuring F_{res} and F_{prop} using ARS other than the VPM and MPM can be categorized by research groups and thus authors. The three primary authors are Clarys, Takagi, and Shimonagata. While other authors come and go, each of the articles discussed will have one of these authors. Interestingly while the methodology of Clarys is stable, the methodologies of Takagi and Shimonagata evolve.

The methodology of Clarys involves measurement of the velocity that can be achieved at maximum effort under a variety of F_{load}s. Both resisting and assisting loads are used to construct a graph of F_{load} vs. velocity as seen in Figure 15 (Kemper, Verschurr, Clarys, & Jiskoot, 1983). Resisting loads are considered as negative values of F_{load} and assisting loads are positive values of F_{load}. Values of F_{load} that do not cause a large deflection of velocity from v_{max} are used to establish a curve between F_{load} and velocity. The shape of this curve was debated in the section on partially tethered swimming. The curve is extrapolated to determine the force required to cause zero velocity. The curve is then translated to set the vertical intercept to the origin. The resulting curve is considered to be the relationship between F_{res} and velocity. In a sense then, the method of Clarys assumes that the relationship between F_{load} and velocity is the same relationship as between F_{res} and velocity. The validity of this assumption is not sufficiently addressed and does not appear to bear any support. The methodology of Clarys has been used to examine the relationship of F_{res} to anthropometric dimensions (Clarys, 1978; Clarys, 1979) and evaluate efficiency when used with oxygen consumption measurements (Kemper, Verschurr, Clarys, & Jiskoot, 1983).

Figure 15

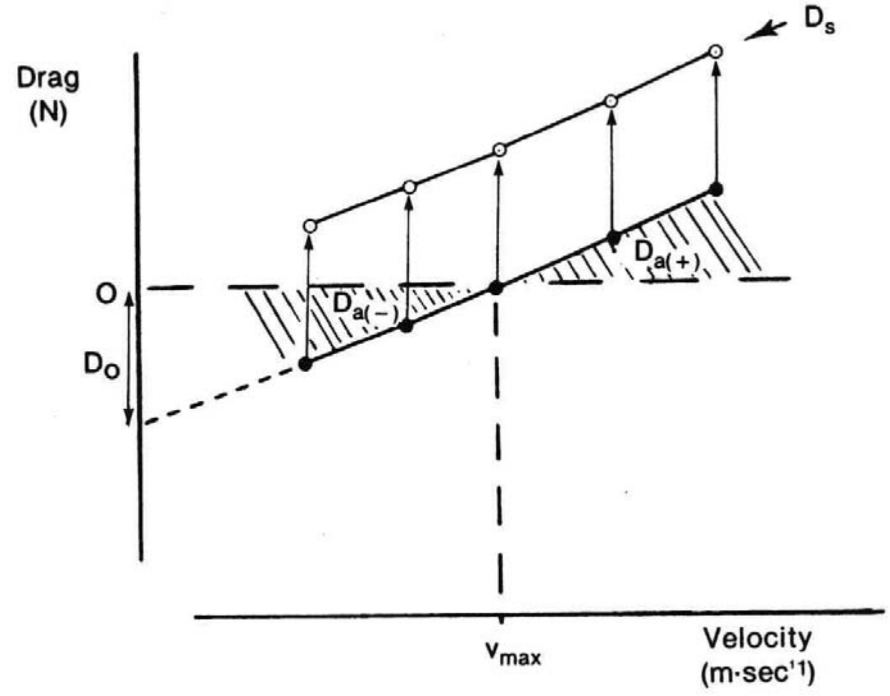


Figure 2—Determination of swimming drag D_s by extrapolation of the drag ($D_{A(+)}$) and added propulsion ($D_{A(-)}$) curve to D_0 at zero velocity.

FIGURE 15 – from Kemper, Verschurr, Clarys, & Jiskoot (1983)

The methodology of Takagi was first introduced by Nomura, Goya, Matsui, and Takagi in 1994. This methodology makes several unusual and unsubstantiated assumptions. First the model used breaks F_{res} into two components: the resistive force experienced by the passive body (F_{pres}) and the resistive force caused by movement of the body (F_{kres}). The Takagi model assumes that the total F_{res} is the sum of these two separate components, $F_{res} = F_{kres} + F_{pres}$. The second assumption is that the propulsive forces remain the same regardless of the relative velocity of the water underneath the body. This leads to the conclusion that the fully tethered force (F_{max}), or a predicted value for F_{max}, is always equal to F_{prop}. This makes the determination of F_{res} simple, $F_{res} = F_{max} – F_{load}$. The theory discussed in the semi-tethered swimming section contradicts this simplistic model. The model goes on to calculate F_{kres} by subtracting out the measured F_{pres} at each velocity. $F_{kres} = F_{max} – F_{load} – F_{pres}$. While various articles using this technique attempt to define the relationship between velocity and F_{res} or F_{kres}, the underlying technique remains the same. Of the four references, three work on developing the technique and equipment (Nomura, Goya, Matsui, & Takagi, 1994; Takagi, Shimizu, & Kodan, 1999; Takagi, Shimizu, Kodan, Onogi, & Kusagawa, 1998) and one applies the measurements to examine the effects of morphological characteristics on F_{res} (Takagi, Shimizu, & Nomura, 1995). The sophistication of the equipment and the specific protocols and calculations are modified throughout the articles, but the faulty underlying assumptions remain the same. Thus the model evolves in complexity without correcting or addressing the fundamental error.

Articles authored by Shimonagata reporting values for F_{res} operate under the same faulty assumptions as those of Takagi. Unlike Takagi, as the articles authored by

Shimonagata progress, the emphasis shifts away from calculations of F_{res} and towards measurement of P_{load} and its characteristics (Shimonagata, Taguchi, & Miura, 2000; Shimonagata, Taguchi, & Miura, 2003; Shimonagata, Taguchi, Taba, Ohshiro, & Miura, 2002). Thus Shimonagata evolves from drawing improper conclusions to reporting only valid values of P_{load} and P_{max}.

As a whole, ARS methods for determining resistive and propulsive forces during swimming require less specialized equipment and are less costly to complete than other methods. ARS methods also tend to take considerably less time to complete. This makes ARS methods for determining resistive and propulsive forces more accessible than other methods. ARS methods are also very flexible and can also be used to test any style of swimming. ARS methods also suffer serious limitations. They tend to be less accurate and less valid than other methods. A number of the ARS methods discussed make flawed assumptions so critical to the models that the results of the model are not interpretable. Furthermore, most of the methods are only capable of measuring F_{res} at v_{max} and have trouble distinguishing between F_{prop} and F_{res}.

Extrapolation of Oxygen Consumption

The extrapolation of oxygen consumption (VO_2) technique was first published in 1972 by DiPrampero, Pendergast, Wilson, and Rennie. The VO_2 extrapolation technique involves the measurement of VO_2 at a set velocity of swimming under a variety of external loads. Constant velocity swimming is achieved using either a flume or an annular pool. During this swimming, VO_2 is measured once the subject has reached a steady state. This procedure is repeated with the addition of either an assisting or resisting load as supplied by a weight and pulley system. If the load is assisting the swimmer, VO_2 decreases. If the load is resisting the motion of the swimmer, VO_2 increases. As the velocity of the water has not changed, the F_{res} of the swimmer has not changed. The F_{prop} of the swimmer, however, will increase if F_{load} is resisting and decrease if F_{load} is assisting. For each Newton of force that is provided in assistance by F_{load}, F_{prop} should decrease by one Newton (Equation 7). Using this model, when F_{load} is assisting the swimmer to a large enough extent F_{prop} should reach 0. Assuming that the metabolic efficiency of the swimmer does not change, this point could be identified when VO_2 equaled resting values. Should this occur, $F_{load} = F_{res}$ and the goal of measurement of F_{res} would be achieved.

Equation 7

$F_{load} + F_{prop} = F_{res}$

This situation is complicated by the fact that efficiency does indeed begin to change once the deviation from the free swimming state become large. An alternative to merely increasing the assisting F_{load} must then be found. This alternative involves the prediction of oxygen consumption using values of F_{load} close to the free swimming condition. Assuming that efficiency doesn't change for small values of either assisting or resisting F_{load}, F_{prop} and VO_2 should be linearly related if the effort is below VO_{2max}. After completing measurements of VO_2 for several small values of F_{load} a graph of VO_2 vs. F_{load} similar to Figure 16 (from Holmer, 1974) can be constructed. Extrapolation of a best fit line of the data to a resting value of VO$_2$ should yield the F_{load} that causes F_{prop} to equal zero. Therefore this value of F_{load} is equivalent to F_{res}.

Figure 16

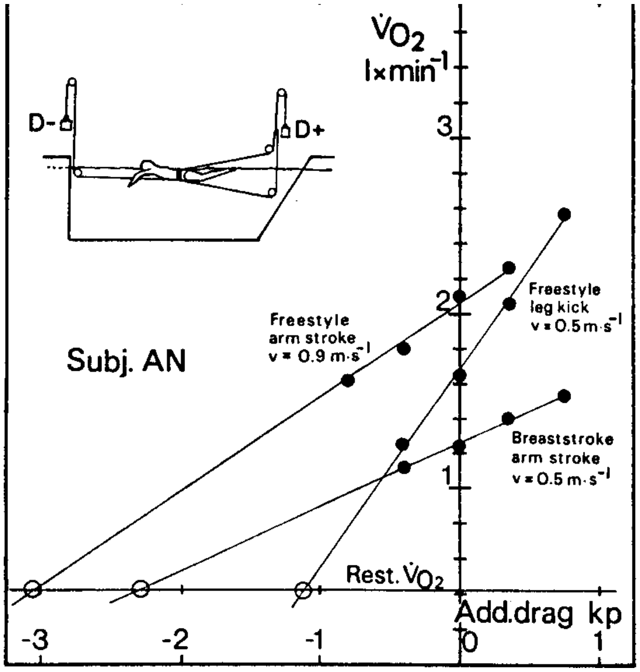


FIGURE 16 – A graphical representation of the VO$_2$ extrapolation technique for determining F_{res} from Holmer (1974)

In addition to defining the method, DiPrampero, Pendergast, Wilson, and Rennie (1972) verified that the relationship between F_{load} and VO$_2$ was linear in the desired range and found preliminary results for 9 subjects at a variety of velocities in breaststroke and front crawl. As the study was primarily descriptive in nature, the experimental design made no comparisons between strokes or velocities, but the authors note wide variability in the values of F_{res}. In 1974, the same authors moved from definition to application of the method by testing 10 subjects doing front crawl at both 0.55 and 0.90 m/s. The article is still mainly descriptive however and evaluates the relation of F_{res} values to other earlier sources as well as discussing the concept of efficiency. Also in 1974, Holmer uses a small population of 3 subjects to examine the differences between arms only, legs only, and whole stroke swimming of both front crawl and breaststroke. As the subject population was limited conclusions can not be reached. In 1974 Rennie, Pendergast, and DiPrampero begin to use the technique to explore the differences between males and females. With larger population, this conference proceeding outlines the results presented in a subsequent article by Pendergast, DiPrampero, Craig, Wilson, and Rennie (1977) which found that for a group of 22 females and 42 males, the males had a significantly ($p < 0.05$) greater F_{res} than the females at each velocity tested from 0.4-1.2 m/s. The article also begins to examine the relationships between F_{res}, underwater torque, and body surface area in an independent groups fashion. Underwater torque is a measure of the rotation away from horizontal in a passive floating position due to differences in the position of the center of buoyancy and the center of mass. Literature using the VO_2 extrapolation technique is then absent for almost 2 decades until 1994 when Ungerechts and Niklas reintroduce the method and present the data for a single subject. Also in 1994, Niklas et al. published an abstract comparing VO_2 extrapolation with the MAD system. In a group of 5 subjects, no significant difference was seen between the F_{res} values of VO_2 extrapolation and the MAD system. The abstract makes reference to the data as being pilot to a larger study, but further results have not been published. Finally, in 1996 Zamparo, Capelli, Termin, Pendergast, and DiPrampero manipulated the underwater torque of individuals using weights and found that F_{res} increased along with underwater torque.

The technique of extrapolation of oxygen consumption to determine F_{res} is still quite underutilized. While the methodology has been developed, it has not be used to answer many questions. As a prime example, the relationship between F_{res} and performance has yet to be addressed using VO_2 extrapolation. In addition to being costly and time consuming to conduct, VO_2 extrapolation suffers from the inability to be used at any velocity that elicits a metabolic rate at or above VO_{2max}. As 10/14 Olympic events take less than two and a half minutes, the VO_2 extrapolation technique can not be applied to the speeds swum. In addition to these difficulties, the validity of the technique has come under fire. The balance of forces exemplified in Equation 7 does not directly relate to metabolic rate in that metabolic rate is equivalent to power, P_{total} to be specific, and not force. In order for VO_2 extrapolation to be valid, metabolic rate must be proportional to P_{prop} as well as P_{total}. Recall that P_{total} depend both upon P_{prop} and P_{kin}, the power that increases the kinetic energy of the water. A change in the ratio of P_{kin} to P_{total} with changes in F_{prop} would cause P_{prop} and metabolic rate to uncouple. In this scenario VO_2 extrapolation technique is flawed (Toussaint, Knops, de Groot, & Hollander, 1990). As the ratio of P_{kin} and P_{prop} to P_{total} has not been evaluated with changes in F_{prop}, this assumption can not be evaluated. The VO_2 extrapolation technique also has advantages over the other techniques used to determine resistive and propulsive forces while swimming. The primary strength of the VO_2 extrapolation method is that it can both measure F_{res} at multiple submaximal velocities and is able to be conducted for any swimming style. This combination of strengths allows for the construction of F_{res} vs. velocity curves for any swimming style including the four competitive strokes.

The MAD System

The Measuring Active Drag (MAD) System has been studied fairly extensively and in a variety of ways. The initial articles describe the methodology and evaluate the relationship of measured values of F_{res} to velocity and to performance. The MAD system was also used to examine differences in F_{res} in different groups and situations. The evaluative techniques of the MAD system were then expanded to attack the problems of efficiency and metabolic rate. Finally, the MAD system has been compared to the other prominent methods of determining F_{prop} and F_{res}.

The first publication using the MAD system was by Hollander, Toussaint, de Groot, and van Ingen Schenau in 1985. While this article found a non-significant relationship between 100 m performance best time and F_{res} at 1.86 m/s for males and 1.63 m/s for females (R = 0.07 and -0.27 respectively), it did not extensively define the methodology, but referenced an article in print likely submitted earlier but published later. The methodology description by Hollander, de Groot, van Ingen Schenau, Toussaint, de Best, Peeters, Meulemans, and Schreurs was published in 1986. The MAD system is composed of a series of pads separated by a constant distance underwater. The pads are connected to a force transducer. As the subject swims front crawl above the pads, they push off the pads and the force of each push off is measured. The force of the hand on the pad is assumed to be the total propulsive force because the rest of the arm is not moving backwards and the legs are restrained. While this may not mimic F_{prop} during free swimming very well, it does give a good indication of the force required to balance F_{res} at that velocity. Thus the force equal and opposite to the force exerted on the MAD system is the measured value for F_{res}. The MAD system as illustrated in the article is shown in Figure 17. Toussaint, de Groot, Savelberg, Vervoorn, Hollander, and van Ingen Schenau (1988) showed one of the strengths of the MAD system by evaluating the relationship between velocity and F_{res} for individual swimmers as well as groups. Using 32 males and 9 females, these authors fit the relationship between F_{res} and velocity to a power function and found F_{res} to be proportional to a power of velocity slightly greater than 2.

Figure 17

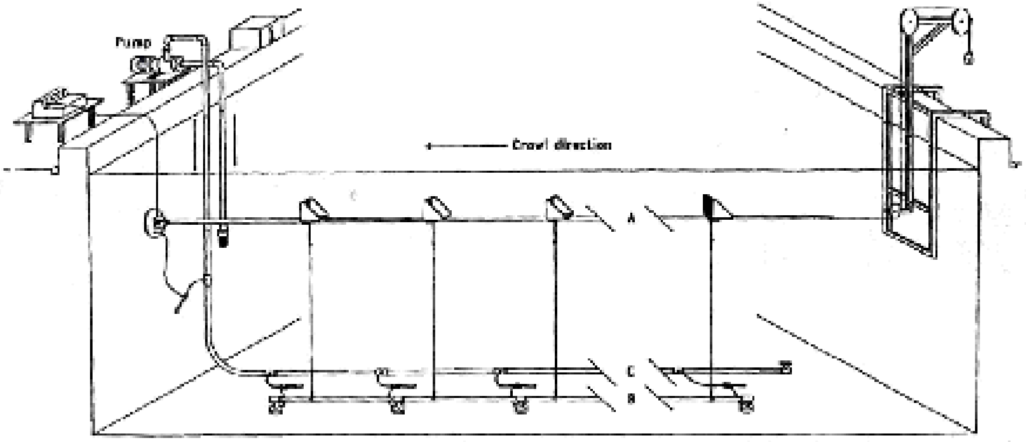


Fig. 1. General view of the system for measurement of propulsive forces during swimming. The left end of tube A contains the force transducer, the right end is used for gauging.

FIGURE 17 – Schematic of the MAD system from Hollander et al. (1986)

Once the methodology of the MAD system had been established, the technique was used to investigate a number of questions. One question examined was the relationship between F_{res} during swimming and the resistive forces experienced during passive towing (F_{pres}). Hollander, Toussaint, and Troup (1989) published an abstract identifying F_{pres} as being both less than F_{res} when done in a streamline position and also highly subject to changes in body position. Merely lifting the head was seen to increase F_{pres} to values three times greater than in the streamline position and also greater than F_{res}. Toussaint, Bruinink, Coster, de Looze, Van Rossem, Van Veenen, and de Groot (1989) examined the perceived advantage of wearing a wetsuit by comparing F_{res} while wearing a wetsuit to F_{res} in a standard swimming suit at velocities of 1.10, 1.25, and 1.50 m/s. Using 8 males (age = 28.50 ± 3.42 years, mass = 81.38 ± 5.21 kg, height = 1.85 ± 0.05 m) and 4 females (age = 22.25 ± 0.50 years, mass = 70.50 ± 8.02 kg, height = 1.80 ± 0.05 m), the authors found that F_{res} was reduced significantly ($p < 0.01$) by use of a wetsuit at all three velocities by an average of 16.1, 14.2, and 12.1 % for 1.10, 1.25, and 1.50 m/s respectively. In 1988 Huijing, Toussaint, Mackay, Vervoorn, Clarys, de Groot, and Hollander investigated the link between F_{res} and body dimensions. This information was published in a conference proceedings and found that F_{res} was significantly correlated with a number of anthropometric measurements including weight ($R = 0.87$) height ($R = 0.55$) and two different estimates of projected body area ($R = 0.84$ and 0.87). The results do lack some credibility in that only 17 subjects were used and correlations of F_{res} with 18 primary and 7 calculated measures of body dimension were made. In 1990 Toussaint, de Looze, van Rossem, Leijdekkers, and Dignum expanded on this study to examine the changes in F_{res} that occur during growth. They found that in a group of 4 boys and 9 girls evaluated at 12.9 and 15.4 years of age, F_{res} did not change over this 2.5 year time period despite increases of an average of 17 cm in height, 14.7 kg in mass, and 16% in cross-sectional area.

As the MAD system can measure F_{res} and therefore P_{res} (the power required to overcome F_{res}), it can also be used to measure efficiency. As originally explained by

Toussaint, Beelen, Rodenburg, Sargeant, de Groot, Hollander and van Ingen Schenau (1988), when using the MAD system, the total efficiency can be broken down into two parts: mechanical efficiency and propulsive efficiency. Mechanical efficiency is described as the ratio of P_{res} to the metabolic power required only to overcome P_{res} and is determined by measuring oxygen consumption during swimming on the MAD system. Propulsive efficiency is defined as the ratio of the metabolic power required only to overcome P_{res} and the metabolic power generated while free swimming at the same velocity. The difference between the two is the power that gives kinetic energy to the water (P_{kin}) and is in a sense wasted. Propulsive efficiency is measured by comparing VO_2 values from swimming on the MAD system and free swimming at the same velocity. The total efficiency is the product of the mechanical and propulsive efficiencies. These techniques were further described by Toussaint, Hollander, de Groot, van Ingen Schenau, Vervoorn, de Best, Meulemans, and Schreurs (1988) and de Groot, Toussaint, Hollander, and van Ingen Schenau (1990). Also in 1990 Toussaint, Knops, de Groot, and Hollander compared the total efficiency of males and females finding that while total efficiency for males is less the females when compared at the same velocity, the total efficiency of males and females becomes the same when standardized for P_{res}. Accordingly, they found that efficiency increases with increases in P_{res}. Toussaint (1990) found that competitive swimmers had greater total efficiency than triathletes.

The validity of the MAD system has also been assessed by comparison with the other prominent methodologies for determining F_{res} (or in the opinion of the authors, the validity of other prominent methodologies has been assessed using the MAD System). Initially this comparison was merely a comparison of the absolute values as found in others publications (van der Vaart, Savelberg, de Groot, Hollander, Toussaint, & van Ingen Schenau, 1987). Later a repeated measures design was used with select methodologies for more accurate assessment. As mentioned in the previous section Niklas, Ungerects, Hollander, Fuhrmann, Hottowitz, Toussaint, and Berger (1994) found no difference between F_{res} from VO_2 extrapolation and the MAD system in an abstract using 5 subjects. Berger, Hollander, and de Groot found that the use of video analysis to determine F_{prop} showed a linear correlation of 0.80 to the F_{res} of the same swimmer at the same velocity as measured by the MAD system. The mean difference of the F_{prop} from video analysis and the matched F_{res} from the MAD system was only 2 N. Finally as discussed extensively in the section on the VPM, Toussaint, Roos, and Kolmogorov (2004) compared the determination of F_{res} using the VPM and the MAD system.

Determination of F_{res} using the MAD system is the most simplistic and yet sophisticated of all of the methods. Despite the lack of environmental validity, it is likely the most valid method of measuring F_{res}. The MAD system also allows for the quantification of the F_{res} vs. velocity relationship. The major shortcoming of the MAD system is the lack of adaptability. The MAD system can only be used to measure front crawl without leg motion. Perhaps the only way in which the MAD system could aid in comparing different styles of swimming would be to aid in the validation of another more versatile methodology.

Video Analysis

Kinematic video analysis differs dramatically from all other methods of determining propulsive and resistive forces during swimming. It is by far the most complicated, time consuming, and error ridden methodology. It is also provides the most environmental validity and can be used to measure any form of swimming without affecting the swimmer in any way. The literature relating to the use of kinematic video analysis to determine propulsive forces is sparse.

Schleihauf is considered to be the founding father of video analysis in swimming. He authored the first article dealing with the subject in 1979. His first step was to measure the lift and drag forces on models of a hand and determine the coefficients of lift and drag for the hand based upon the angles of orientation. He also examined the effects of the spread of the fingers and the thumb position. Once the characteristics of the hand had been adequately defined, Schleihauf used three conditions in an attempt to validate the measurements. Using two cameras and a pseudo 3 dimensional analysis, he analyzed a single vertical sculling motion and single tethered strokes for both breaststroke and front crawl. In the tethered swims, the calculated F_{prop} could be compared with F_{load}. For the vertical scull the net force was assumed to be zero, and therefore F_{prop} should equal the difference between the buoyancy force and the force of gravity. These three trials showed reasonable agreement between video analysis and the expected F_{prop}. Schleihauf then applied this methodology to a small number of subjects during free swimming. In 1983 Schleihauf, Gray, and DeRose refined the technique by using a model of both the hand and the forearm. The authors also upgraded to a three dimensional analysis, although this analysis was not true 3D DLT and was therefore less accurate. In addition to examining F_{prop}, the authors also began to look at the torques on the wrist, elbow, and shoulder. Continuing to develop the methodology Berger, de Groot, and Hollander (1995) refined and updated the lift and drag coefficients in hand and forearm models.

The work of Schleihauf (1979), Schleihauf, Gray, and DeRose (1983), and Berger, de Groot, and Hollander (1995) is developmental and neither the random error in the measurement nor the were systematically assessed. In 1995, Payton and Bartlett set about to determine the random error associated with video analysis. Ten experienced investigators analyzed a single stroke of breaststroke using 3D DLT. Errors in digitizing the angular arrangement of the hand led to 27% and 20% error in the calculation of the lift and drag coefficients of the hand. The combination of these errors with a 6% error in the estimation of hand speed led to a total random measurement error of 26% in F_{prop}. The suggested solution to reduce the error was the use of multiple investigators. While this is a useful suggestion the time requirements are unpractical. The validity of the use of kinematic video analysis to determine F_{prop} during swimming was also evaluated using the MAD system by Berger, Hollander, and de Groot (1999) as discussed in the previous section.

Determination of propulsive forces during swimming using kinematic video analysis is the most environmentally valid methodology. It requires no modifications or considerations on the part of the subject to the extent that it might be possible to use during competition. Kinematic video analysis is also versatile enough to measure any style of swimming. However, it is likely that video analysis will never reach the stage of development required to accurately assess F_{prop} for any style of swimming. Kinematic video analysis rapidly become very complicated when each body part that may be propulsive is taken into account. For example, the effects of the upper arm and the legs have yet to be modeled to determine lift and drag coefficients. Furthermore, the large number of variables that are necessary to describe the conformation of the human body are unwieldy. The large number of variables leads to both large systematic and random error and the complication grows exponentially with each new body part which is considered. In addition to the inherent error, the time requirements for analysis undermine the practicality of this methodology.

Conclusion

Each of the four methodologies offer a unique group of strengths and weaknesses. ARS methods are accessible and versatile, but suffer from limitations in validity, accuracy, and interpretation. VO_2 extrapolation is time consuming, expensive, and cannot be used to evaluate velocities in the realm of most competitive events. On the other hand, VO_2 extrapolation is versatile and can be used to establish the relationship between F_{res} and velocity for individuals and groups. The MAD system is considered to be the most valid and accurate method for determining F_{res}, but lacks versatility as it can only be applied to front crawl with restrained legs. Video analysis is the most environmentally valid measure, but the inherent error and the time requirements make it unpractical at the current time. Each method has its place based upon the designs of the researcher. Two ARS methods were chosen for the proposed study for their accessibility and versatility. The proposed study hopes to improve the difficulties in validity, accuracy, and interpretation currently plaguing ARS methods.

Conclusion

The choice of ARS methodology for the proposed study in comparison with the alternate methods for determining resistive and propulsive forces during swimming was based upon the accessibility to both a scientific and coaching community. The Velocity Perturbation Model is the most widely used and evaluated ARS model. While the VPM is established, evidence of the validity is not conclusive. The weaknesses of the VPM were elucidated in this review of literature. The Max Power Model avoids some of the errors in assumption of other ARS models by purporting to provide a quantitative comparison of values of F_{res} and F_{prop} without estimating the values. The face validity of the MPM was established through this review of literature. The proposed study aims to develop the validity of the MPM as well as furthering the evaluation of the validity of the VPM and comparing the results of the two.

CHAPTER 3: METHODOLOGY

Introduction

The goal of this study was twofold. First, a new method (the Max Power Model) for measuring resistive and propulsive forces using assisted and resisted swimming was developed. This development was accomplished in three ways: examination of the shape of the P_{max} vs. v_{max} curve, development of a method of comparing P_{max} vs. v_{max} curves, and finally testing the sensitivity of the method to large changes using the four competitive strokes and underwater dolphin kicking. Second, the responses of the Max Power Model (MPM) and the Velocity Perturbation Model (VPM) to independent changes in resistive and propulsive forces during swimming was examined in an effort to assess the validity of both models. Outlined below are detailed descriptions of the testing protocol, the treatments, the subject population, and the statistical analysis used to answer the research questions.

Testing Protocol

The testing protocol had two phases. The initial protocol was used to address the topic of development of the Max Power Model. Based upon analysis of the results from this initial protocol, the protocol was refined in an effort to produce more accurate and precise measurements to facilitate detection of small differences. This revised protocol was used to assess the validity of the MPM and the VPM.

The Initial Protocol

Prior to testing, the height and mass of each subject was measured and age was self reported in order to describe the subject population. The testing was composed of two measurements: v_{max} and P_{max}. Each measurement is described in detail in the following sections.

v_{max}

To determine v_{max}, the time required to complete the middle 13.72 m (15 yd) during a 22.86 m (25 yd) maximal effort swim was measured using hand timing with a stopwatch. The distance timed was measured by travel of the head of the swimmer. Timing commenced when the head was 4.57 m (5 yd) away from the wall in order to minimize the effect of the push off on the velocity. v_{max} was calculated by dividing the 13.72 m distance by the time required to travel that distance. The 25 yd maximal effort swim was completed twice with the average of the two measurements used for v_{max}.

While hand timing is not the most accurate method of determining velocity it was chosen for its accessibility to both scientists and coaches. In order to truly to be accessible to coaches, the equipment used must be inexpensive and non-technical.

P_{max}

P_{max} was determined using a series of maximal effort swims with a progressively increasing F_{load} supplied by a modified Power Rack (Total Performance Inc., Mansfield OH). This testing was based on the methodology of Hopper (1981). Each of between 5 and 15 trials completed with a different F_{load} allowed for a calculation of the power delivered to the external load (P_{load}) as the product of F_{load} and velocity. As F_{load} was increased, P_{load} increased and then decreased showing a local maxima (P_{max}) as discussed in Chapter 2. P_{max} was defined as the maximum value for P_{load}. Details of v_{max} measurement and F_{load} application as well as the specific testing protocol used follow.

Velocity

To determine the velocity of each trial, the time required to complete 10 m during a 14 m maximal effort swim was measured using hand timing with a stopwatch. The distance was measured by the travel of the head of the swimmer and timing commenced when the head was 3.45 m away from the wall in order to minimize the effect of the push off on the velocity. Velocity was calculated by dividing the 10 m distance by the time required to travel that distance.

F_{load}

The Power Rack is a weight and pulley system designed for use while swimming. The unmodified Power Rack has a travel distance for the swimmer of approximately 10 m and a mechanical advantage of 5:1. The Power Rack was modified by replacement of the pulleys to gain a greater travel distance. Pulleys of different sizes were used requiring independent wires for the two different pulley sizes. The wire for the larger pulley wrapped over itself on the pulley. As a result the size of the pulley, the mechanical advantage of the pulley system, and the force against the swimmer changed as the swimmer moved away from the system. The mechanical advantage of various Power Racks at various points ranged from approximately 7:1 to 10:1 and the total travel distance available to the swimmer was approximately 15 m. The load was manipulated by adjusting the number of 22.3 N plates lifted by the system. The average force (F_{load}) over the 10 m velocity measurement distance was assessed using a force transducer for a number of different plate settings. As the error in the force measurement was judged to be larger than the deviation in weight of the plates, the average force for each plate setting was plotted against the number of plates and a best fit regression line was computed. The regression equation was used to predict the F_{load} for each plate. In some cases an additional large weight “saddle bags” was added to allow for larger required F_{load} values. In this case the calibration procedure was repeated with the additional weight. A table of the calibration values for each of the Power Racks used is included in Appendix A.

Testing Protocol

The test commenced with an F_{load} of between 30 and 40 N. Subjects received approximately 1 to 1.5 minutes rest between each trial. Throughout the series of trials, F_{load} was modified. F_{load} was increased for each trial, rapidly at first, but by approximately 4 N each trial near the power peak. The test was stopped when it was judged by the experimenter that the power peak had been exceeded. Tests in which the power did not peak (decrease with an increase in F_{load}) were excluded from analysis. The largest value of P_{load} from this series of trials was identified as P_{max}.

The Revised Protocol

In an attempt to increase the accuracy and precision of the P_{max} and v_{max} measurements, methodological concerns from the initial protocol were addressed by the revised protocol. The third portion of the study was attempting to detect what were anticipated to be smaller treatment effects. Therefore, despite the low random error of the initial protocol (as evidenced by the strong relationships observed) methodological improvements were deemed well advised. Furthermore, the addition of the VPM analysis made special requirements on the data collection procedures that were satisfied by the revised protocol.

The first methodological change was in the modifications made to the Power Rack. Instead of using pulleys of different sizes as in the initial protocol, the distance of travel available to the swimmer was increased by increasing the height of the Power Rack by 1.5 m, from approximately 2.15 to 3.65 m. This change also had the added benefit of decreasing the mechanical advantage of the system back to 5:1 allowing for increases in the available F_{load}. This increase in available F_{load} was particularly important for the treatment conditions that involved increased F_{prop} and decreased F_{res}.

The second methodological change was made to improve the accuracy of the timing. In the initial protocol, the timing was done by hand with a stopwatch. In order to improve accuracy, the revised protocol used a computer based timing system for both v_{max} and P_{max} trials. To time the v_{max} trial, two digital cameras (Canon GL-2 or Canon ZR-90) were attached via firewire to a laptop running Simi Motion software. Simi Motion synchronized the cameras to the nearest frame setting the accuracy at 0.0167 s. As the accuracy of the trial was increased, the number of trials for v_{max} was decreased from two to one. The velocity of the trials using the Power Rack were timed using a single camera (Canon GL-2). The camera was focused on the weight stack and calibrated based on a known distance. The movement of the weight stack was digitized using a marker ball. Simi Motion reported the distance traveled during each 60th of a second. Velocity was calculated from the known distance and time.

The third methodological change was to standardize the length of each sprint used in the P_{max} testing based upon time instead of distance as in the initial protocol. As F_{load}

increased and velocity decreased, the duration of the effort increased using the initial protocol. Any changes in velocity due to metabolic power changes would be based on the amount of time elapsed during the effort. For this reason, standardizing the length of the sprint based on time was thought to improve the accuracy of the measurement. Calculation of velocity with Simi Motion had the added benefit of allowing for standardization based on time. Velocity of the marker ball was averaged for three seconds beginning two seconds after the point at which instantaneous velocity peaked (assumed to be the point at which the swimmers feet left the wall). In order to regulate the total duration of the effort, the swimmer was asked by the experimenter to complete a set number of strokes. The number of strokes was determined by the experimenter to ensure that at least 5 seconds of effort would be completed during each trial.

The fourth methodological change was to standardize the rest interval. As opposed to the initial protocol which was conducted in a field study environment, the revised protocol was a much more controllable situation. As a result the rest period could be standardized and the swimmers were instructed to begin one trial every two minutes.

The fifth methodological change was designed to decrease the total number of trials required to find P_{max} without decreasing the resolution of the P_{load} vs. velocity curve around P_{max}. P_{load} was approximated following each trial using hand timing. The P_{load} vs. velocity curve was first scanned with low resolution using large differences between successive F_{load}s (~20 N). Once the F_{load} range in which P_{max} was located was isolated, F_{load} was modified in smaller increments (as small as 4 N) in order to find P_{max}.

The sixth and seventh methodological changes to the initial protocol were made to bring the testing protocol closer to the original methodological determination of the

VPM. Inspiring the sixth change, the VPM requires a trial with approximately 10% decrease in velocity from v_{max}. The most appropriate F_{load} and thus velocity for use with the VPM was found at the beginning of the testing protocol by very slowly increasing F_{load} initially and continuing to do so until a greater than 10% velocity decrease was seen (always requiring less than 4 plates). Inspiring the seventh change, in the original methodology of the VPM the velocities of the unloaded and loaded trials were the same distance. For this reason the distance over which v_{max} was measured was shortened to 8 m beginning 4 m from the wall.

The eighth and final methodological change required the swimmer to wear the same tethering belt during the v_{max} testing as during the power testing. As the methods being examined are designed to detect differences in F_{res} and the belt may affect F_{res}, it was logical to standardize the belt across trials.

Besides these eight changes designed to increase accuracy and precision, the revised protocol and initial protocol were identical. The calibration information for the redesigned Power Rack is included in Appendix A.

Treatments

Three subject groups were formed for testing. Groups one and two were used to develop the MPM. The first group was tested using the initial protocol in front crawl and was used to determine the shape of the P_{max} vs. v_{max} curve. The second group was also tested using the initial protocol with subjects completing the v_{max} and P_{max} tests in butterfly, backstroke, breaststroke, and underwater dolphin kick. The third and final group was tested using the revised protocol in order to assess the validity of the MPM.

Developing the MPM

Subjects in groups one and two were tested once. The first group completed v_{max} and P_{max} testing in front crawl. The second subject group completed the same testing in their choice of any competitive stroke (besides front crawl) or underwater dolphin kick.

Assessing the validity of the MPM

The final subject group was tested a total of 5 times in a repeated measures format. All five treatments consisted of front crawl swimming. The control treatment was normal front crawl swimming wearing a standard brief suit (subjects wore the same swim suit, cap, and goggles over all of the treatment conditions). Two of the treatments were used to manipulate propulsive force without affecting resistive force. TYR Catalyst Brites medium size hand paddles (TYR Sport Inc., Huntington, CA), which functionally increase the size of the hand, were used to increase F_{prop} and Swim Fist Training Gloves (Adolph Keifer and Associates, Zion, IL), which functionally restrict the size of the hand, were used to decrease F_{prop}. Two of the treatments were used to manipulate resistive force without affecting propulsive force. A pocketed mesh drag suit (Adolph Keifer and Associates, Zion, IL) was used to increase F_{res} and an Xterra Ventilator Sleeveless Wetsuit (Xterra Wetsuits USA, Richmond, VA) was used to decrease F_{res}. The treatments were administered in random order over three days with two treatments administered on each of the first two days and the final treatment on the third day.

Subject Population

The subjects were competitive swimmers from the Midwest and were recruited from high school, college, and club swimming teams and at swimming instruction camps.

The subjects used to develop the MPM were both males and females with a wide range of ages. The subjects used to assess the validity of the MPM were all males between the ages of 20-28. The subject population was narrowed to males only and the age range was narrowed in order to eliminate possible confounding variables to aid in detection of smaller differences. Tables 1 and 2 below describe the subject populations used to develop the MPM and to test the validity of the MPM respectively. Individual data is presented along with the v_{max} and P_{max} testing results in Appendix B.

Table 1

Stroke	Sex	N	Age (yrs)	Height (cm)	Mass (kg)
Butterfly	M	7	16.6 ± 3.7	174.1 ± 9.9	70.7 ± 15.7
	F	2	16.5 ± 2.1	171.1 ± 1.7	75.2 ± 8.3
Backstroke	M	8	17.9 ± 3.3	176.7 ± 21.7	75.3 ± 15.6
	F	4	14.0 ± 3.2	162.8 ± 11.4	53.7 ± 14.2
Breaststroke	M	5	14.7 ± 4.2	167.2 ± 16.1	54.8 ± 20.5
	F	4	14.7 ± 3.8	167.3 ± 4.6	55.6 ± 11.9
Front Crawl	M	105	15.6 ± 2.7	171.9 ± 13.0	64.2 ± 14.8
	F	178	13.9 ± 2.9	160.5 ± 11.3	54.6 ± 13.2
Dolphin Kick	M	10	21.4 ± 1.8	180.2 ± 4.4	79.3 ± 6.2
	F	4	23.0 ± 3.7	165.9 ± 6.6	64.8 ± 2.4

TABLE 1 - A description of the subject population used to develop the MPM divided by stroke

Table 2

Sex	N	Age (yrs)	Height (cm)	Mass (kg)
M	10	24.4 ± 3.0	181.1 ± 8.3	77.7 ± 15.3

TABLE 2 - A description of the subject population used in the repeated measures format to assess the validity of the MPM

Statistical Analysis

The statistical analysis used to answer each of the research questions is listed below in the three sub-study categories determined in Chapter 1. Each research question and hypothesis is restated and followed by the analytical procedure.

Determination of the shape of the relationship between P_{max} and v_{max} for front crawl and development of a method of comparing P_{max} vs. v_{max} curves

Question: What function (of linear, power, and exponential) best describes the relationship between the maximum power delivered to an external load (P_{max}) and the maximum free swimming velocity (v_{max}) during front crawl swimming?

Hypothesis: A power function will best describe the relationship between P_{max} and v_{max} during front crawl swimming.

Analysis: The best function to describe the relationship between P_{max} and v_{max} was determined by a comparison of the R values for the correlations using a series of t-tests developed by Hotelling (1940).

Question: What statistical method can be used to test for differences in the relationships of P_{max} vs. v_{max} between different treatments, swimming styles, and anthropometric qualities?

Hypothesis: A transformation of v_{max} based upon the power function will allow linearization of the relationship between P_{max} and v_{max}. Comparison of the P_{max} v_{max} relationship between treatments, swimming styles, and anthropometric qualities can then be accomplished using ANCOVA with the transformed v_{max} variable as the covariate.

Evaluation of the relationship of P_{max} vs. v_{max} for the four competitive strokes and underwater dolphin kick

Question: Does the relationship between P_{max} and v_{max} differ for the four competitive strokes and underwater dolphin kick?

Hypothesis: The relationship between P_{max} and v_{max} will differ for the four competitive strokes and underwater dolphin kick. Breaststroke will have the greatest ratio of P_{max} to v_{max} and underwater dolphin kick will have the smallest ratio of P_{max} to v_{max} with the other three strokes falling in between.

Analysis: The relationships between P_{max} and v_{max} were compared based on the procedure developed in the first sub-study. All pairwise comparisons in the ANCOVA were made post-hoc using a bonferonni adjustment to maintain the experiment wide error rate at $\alpha = 0.05$.

Examination of the validity of the Max Power Model using independent modification of the resistive and propulsive forces and comparison with the Velocity Perturbation Model

Question: Does the P_{max} vs. v_{max} relationship differ between standard front crawl swimming and 4 equipment treatment conditions during front crawl swimming: hand paddles, fist gloves, a pocketed drag suit, and a wet suit?

Hypothesis: Normal swimming and the use of hand paddles and fist gloves will all result in the same relationship between P_{max} and v_{max}, however paddles increase both the P_{max}

and v_{max} of an individual and fist gloves decrease both of the variables. Normal swimming has a different relationship between P_{max} and v_{max} than does the use of a pocketed drag suit or a wet suit. When compared to normal front crawl swimming, the use of a pocketed drag suit decreases both P_{max} and v_{max} and also increases P_{max} relative to v_{max}. When compared to normal front crawl swimming, wearing a wet suit increases both P_{max} and v_{max} and also decreases P_{max} relative to v_{max}.

Analysis: Differences in P_{max} and v_{max} were analyzed using planned comparisons for a repeated measures ANOVA. These planned comparisons take the form of paired t-tests (Keppel & Wickens, 2004) $\alpha = 0.05$. The relationships between P_{max} and v_{max} were compared based on the procedure developed in the first sub-study. Planned comparisons in the form of ANCOVAs ($\alpha = 0.05$) were used to evaluate difference between each treatment and standard front crawl swimming.

Question: What is the relationship between P_{max} and F_{res} obtained from the Velocity Perturbation Model?

Hypothesis: The relationship between P_{max} and F_{res} obtained from the VPM will be quadratic, but with a low level of agreement due to the large level of random error in the VPM.

Analysis: Correlations coefficients for linear, power, and polynomial fits were calculated between P_{max} and F_{res} of the VPM. The fits were compared against theoretical expectations.

Question: Can the Velocity Perturbation Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The VPM can not distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Analysis: Differences in the coefficient of drag (k) between the standard and equipment treatments were analyzed using planned comparisons for a repeated measures ANOVA. These planned comparisons take the form of paired t-tests (Keppel & Wickens, 2004) $\alpha = 0.05$.

Question: Can the Max Power Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The MPM can distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Analysis: This analysis is based on the statistical procedures used to answer the previous research questions.

Conclusion

The outlined testing procedures, treatment conditions, subject descriptions, and statistical analysis provide a detailed explanation of how the research questions of the study were answered.

Max Power Delivered to External Load Related to Max Velocity in Front Crawl Swimming

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ABSTRACT

Purpose: The purpose of this study was to examine the relationship between the maximum power that can be delivered to an external load (P_{max}) and the maximum velocity (v_{max}) of swimmers during front crawl. **Methods:** 178 female and 105 male competitive swimmers of varied age, experience, and ability completed tests to determine v_{max} and P_{max}. v_{max} was determined from the average time of two 13.72 m (15 y) maximum effort swims. Power delivered to an external load (P_{load}) was measured at a number of resisting loads using the average velocity over a 10 m maximal effort swim against a weight and pulley system. The external load was progressively increased until a peak was seen and P_{max} could be identified. **Results:** P_{max} during front crawl swimming has a strong linear correlation ($R = 0.879$, $P_{max} = 104.6v_{max} - 111.1$) to v_{max}, but the relationship is more appropriately described by a power or exponential function ($R = 0.926$, $P_{max} = 8.861v_{max}^{3.785}$ & $R = 0.927$, $P_{max} = 0.637e^{2.76v_{max}}$ respectively). The power and exponential correlation coefficients were significantly greater than the linear correlation coefficient ($p < 0.01$) and were not significantly different than one another. **Conclusions:** The relationship between P_{max} and v_{max} is similar to that of velocity and active drag forces in that increases in velocity and v_{max} require disproportionately large increases in active drag and P_{max} respectively. Comparison of P_{max} vs. v_{max} relationships should be made using data linearized by use of a plot of the natural log of P_{max} vs. v_{max}.

Key Words: RESISTED SWIMMING, TETHERED SWIMMING, ACTIVE DRAG, SPRINT SWIMMING

INTRODUCTION

The study of swimming against an external resisting force such as a tether is one of the most available and often studied areas of swimming related research. In 1912, Houssay (5) examined the concept of power delivered to an external load (P_{load}) and identified the presence of a local maxima (P_{max}). Later literature on the relationship between P_{max} and v_{max} primarily consists of linear correlations with little attention to the shape of the curve. In general, large linear correlations are shown between P_{max} and v_{max}. Several authors have reported significant linear correlations between P_{max} and v_{max} of 0.87 (7), 0.87 (11), and 0.92 (12). While the linear correlations are strong, the shape of the curve was not examined.

Insight on the non-linearity of the relationship is found in literature sources mentioning disproportionate differences in P_{max} and v_{max}. Costill, Rayfield, Kirwan, and Thomas (2) report that following 8 weeks of swimming and strength training, P_{max} increased 9.6% while v_{max} increased only 4.0%. This difference could be attributed to either changes towards lower swimming efficiency, which is counterintuitive, or a non-linear relationship between P_{max} and v_{max}. Craig and Boomer (3) note that P_{max} for females was 30% less than males while v_{max} was only 10% less. While the authors suggest this to be indicative of a difference in the P_{max} to v_{max} relationship between males and females, it could also be an indication that the P_{max} vs. v_{max} relationship is not linear.

The purpose of the present study was to examine the linearity of the relationship between P_{max} and v_{max} in front crawl swimming. Based upon the information presented above, it was hypothesized that despite the high linear correlation, the relationship is non-linear and can be better described by a power or exponential fit.

METHODS

Subjects. A total of 283 competitive swimmers of a variety of ages and abilities participated in the study. The study was approved by the Indiana University Human Subjects Committee and written informed consent was obtained from each subject and a parent or guardian if the subject was a minor. The age, height, and body mass of each subject was obtained in order to describe the subject population (Table 1).

Procedure.

v_{max}. The maximum front crawl swimming velocity (v_{max}) of the subject was determined over 13.72 m. Each subject completed two 22.86 m swims at maximal effort. In order to remove the effect of the wall push off and finish on the velocity, the first and last 4.57 m were not timed. The time required for the head of the swimmer to complete the middle 13.72 m of the each swim was measured by hand timing with a stopwatch and velocity was calculated using the known distance and time. The average velocity of the two swims was used as v_{max}.

P_{load}. The power delivered to an external load (P_{load}) was measured from a series of 10 m maximal effort swims with the subject attached via a waist belt to a weight and pulley system. Each subject completed 15 m swims at maximal effort against a variety of external loads. In order to remove the effect of the wall push off, the first 3.45 m of the swim were not timed. The time required for the head of the swimmer to complete the next 10 m of the each swim was measured by hand timing with a stopwatch and velocity was calculated using the known distance and time. The external load was applied via a modified Power Rack (a weight and pulley system from Total Performance Inc. modified by Jerden Industries). The average force at different plate settings was calibrated over the 10 m measurement zone using a force transducer. P_{load} was calculated as the product of the force of the external load and the velocity of the swimmer.

P_{max}. A plot of external resistive load vs. the velocity attained at this load during maximal effort is commonly accepted to be linear for an individual swimmer (1, 2, 10, 11). It follows then, that the P_{load} vs. velocity curve is parabolic for each subject. P_{load} was measured for progressively increasing loads until a peak was observed. P_{max} was defined as the largest measured P_{load}.

Statistical Analysis. Statistical analysis was used to evaluate the correlations of different functions of v_{max} with P_{max}. P_{max} vs. v_{max} was fit with linear, power, and exponential fit. The correlational coefficients of the different fits were compared using a t-test (6) $\alpha = 0.01$.

RESULTS

Comparisons of Fit.

Visual examination of the plot of P_{max} vs. v_{max} in Figure 1 shows a systematic deviation from linearity. Furthermore, while theory predicts both the P_{max} and v_{max} intercepts to be at 0, the linear fit deviates significantly ($p < 0.01$) from this with a P_{max} intercept at -111.1 W. The power and exponential models both demonstrated significantly larger ($p < 0.01$) correlations of $R = 0.926$ and 0.927 than the linear model while not differing from one another. Distinguishing between the power and exponential models is difficult not only in terms of the goodness of fit, but also through visual inspection.

Method of Group Comparison for P_{max} vs. v_{max}.

Based on the strong relationship between v_{max} and P_{max}, comparison of P_{max} between groups or swimming styles can be greatly enhanced by taking v_{max} into consideration. Knowledge of the shape of the P_{max} vs. v_{max} curve is crucial for proper analysis. Based on the results of the current study a natural logarithmic transformation of P_{max} is appropriate to linearize the P_{max} v_{max} relationship. After linearization, the slope of the line is the exponent (b) and the intercept of the line is the natural log of the coefficient (a) as seen in Equations 1 and 2. If the slopes of $\ln(P_{max})$ vs. v_{max} for two groups are similar, use of ANCOVA is appropriate to determine if differences exist. Otherwise, the slopes can be compared using a t-test (14).

Equation 1

$P_{max} = ae^{bvmax}$

Equation 2

$\ln(P_{max}) = \ln(a) + bv_{max}$

As an example, while direct comparison of the P_{max} of males and females using a t-test results in significant differences ($p \leq 0.01$) (Table 2), this finding is clouded by a corresponding significant difference seen in v_{max}. Linearization yields similar slopes (2.60 vs. 2.71 for females and males respectively) appropriate for use with ANCOVA, based upon a non-significant interaction between sex and slope (Figure 2). ANCOVA shows a significant difference between males and females ($p < 0.01$) of 3.687 vs. 3.581 for $\ln(P_{max})$ as evaluated at $v_{max} = 1.476\ ms^{-1}$. This difference can be converted back into values of P_{max} (correcting for the difference between the geometric mean of the logarithmic scale and the arithmetic mean of the normal scale using the consistent estimator I (4)) and is equivalent to a difference of approximately 10%, 40.82 W vs. 36.95 W.

DISCUSSION

The linear correlation of $R = 0.879$ between P_{max} and v_{max} observed was very similar to previous reported values of 0.87, 0.87, and 0.92 (8, 11, 12). It is clear, however, that the relationship between P_{max} and v_{max} is not linear and is more aptly represented by a power or exponential fit. This information is essential in properly comparing groups.

The exponential relationship can account for the differences in gain in P_{max} and v_{max} reported by Costill, Rayfield, Kirwan, and Thomas (2). Eight weeks of strength and swimming training resulted in a 9.6% increase in P_{max}, but only a 4.0% increase in v_{max} (2). If the relationship between P_{max} and v_{max} is assumed to be linear, these results suggest that the swimmers became less efficient in their use of propulsive power. However with the knowledge that the P_{max} v_{max} relationship is exponential, the variation in improvement is logical.

Returning to the example of sex differences, similar to the 10% difference reported by Craig and Boomer (3), females in the current study had a v_{max} of 11% less than the males. While Craig and Boomer (3) found a difference in P_{max} of 30%, the current study found a difference of 42%. Assuming that the P_{max} vs. v_{max} relationship is linear implies that a female swimmer with the same v_{max} as a male can generate either 20% or 31% less power (based on the data of Craig and Boomer (3) or the current study respectively). Treating the relationship between P_{max} and v_{max} as exponential, this difference is reduced threefold from 31% to 10%.

Interpretation of the meaning of P_{max} is debatable. Logically, it is related to the propulsive forces generated by the swimmer. The non-linearity of the relationship between P_{max} and v_{max} strengthens this argument. As velocity rises, the drag forces against the swimmer increase approximately proportionally to the square of the velocity. Accordingly, the propulsive forces required to reach each velocity must increase proportionally to the square of the velocity. The relationship between P_{max} and v_{max} may then allow some insight into both propulsive and active drag forces experienced by swimmers.

While a calculation of active drag forces or propulsive forces is not possible, comparison of these forces is conceivable. Comparison of males and females is not only an example of this, but also lends credence to the concept. Sources from several different methods purported to calculate active drag give indications that females experience smaller active drag forces than males at the same velocity. The ratio of male to female active drag forces in the literature is similar to the ratio of P_{max} values found in the present study. Comparisons can be made using the adjusted means of the ANCOVA showing that at 1.48 ms^{-1}, females on average generate 90% of the P_{max} of males. Pendergast, DiPrampero, Crag, Wilson, and Rennie (9) measured active drag during front crawl swimming using VO_2 extrapolation and found that in the highest measured range of velocities (1.1-1.2 m/s) males experienced drag forces of 80.4 ± 8.8 N while females experienced only 68.6 N ± 7.8 N or 85% of that experienced by the males. Using the equations for calculating the average active drag forces on men and women from the Measuring Active Drag System (MAD System), the force of active drag for both men and women were calculated at approximately the velocity for the means in the ANCOVA used in this study (13). At a velocity of 1.5 ms^{-1}, these results indicate that males experience drag forces of 68.27 N while females experience 51.42 N or ~75 % of those experienced by males. Finally, data obtained using the velocity perturbation model (VPM) (8) for subjects with v_{max} = 1.45 ms^{-1} indicates that the active drag forces on females are approximately 106% of those on males. While this result is contradictory to the others, examination of the VPM data at other velocities shows a trend for lower active drag forces for females than males (8). In conclusion, comparisons of the P_{max} vs. v_{max} curve between females and males show similar results to comparisons of active drag forces in the literature found using a variety of methodologies.

In continuing this line of research it is important to both increase the scope of the measurements and to determine the mechanisms behind the relationship of P_{max} to v_{max}. For instance, characterizing the nature of the relationship between P_{max} and v_{max} while swimming the four competitive strokes might shed further light on this subject in addition to increasing our basic knowledge of the P_{max} v_{max} relationship.

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We would like to thank Jim Steen of Total Performance Inc., Bill Jerden of Jerden Industries, and Dave Tanner for help in supplying materials, constructing, testing, and calibrating the equipment used. We would also like to thank all of the subjects and the numerous data collectors that helped make the large amount of data collection possible.

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CONFLICT OF INTEREST

There is no conflict of interest to disclose for this paper.

Table 1

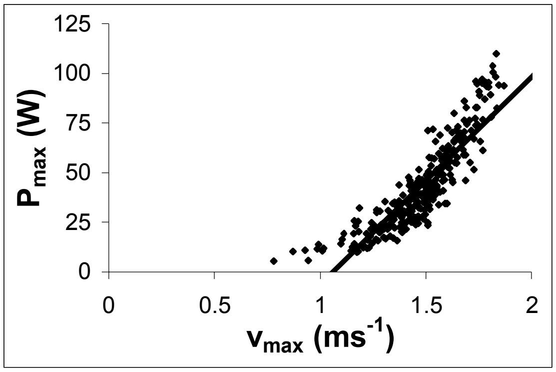
Sex	Age (yrs)			Height (cm)			Mass (kg)		
Female	13.9	±	2.9	160.5	±	11.3	54.6	±	13.2
Male	15.6	±	2.7	171.9	±	13.0	64.2	±	14.8

Table 2

Sex	N	P_{max} (W)			v_{max} (ms^{-1})		
Female	178	33.9*	±	15.1	1.412$^+$	±	0.171
Male	105	59.4*	±	24.3	1.586$^+$	±	0.171

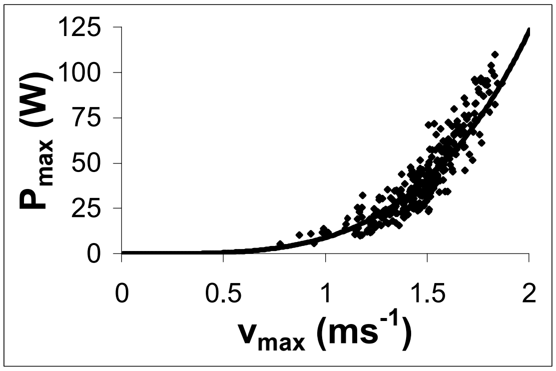
* $^+$ significant differences found using t-test ($p < 0.01$)

Figure 1



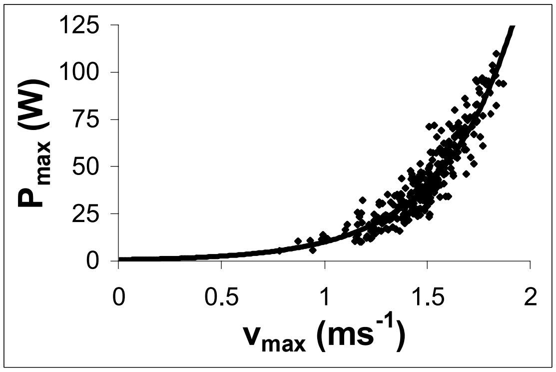
Linear Fit

$P_{max} = 104.6v_{max} - 111.1$
R = 0.879



Power Fit

$P_{max} = 8.861v_{max}^{3.785}$
R = 0.926



Exponential Fit

$P_{max} = 0.637e^{2.76vmax}$
R = 0.927

FIGURE 1 - A comparison of fits for the maximum power delivered to an external load (P_{max}) vs. maximum free swimming velocity (v_{max}). The power and exponential functions have significantly greater correlations than the linear function.

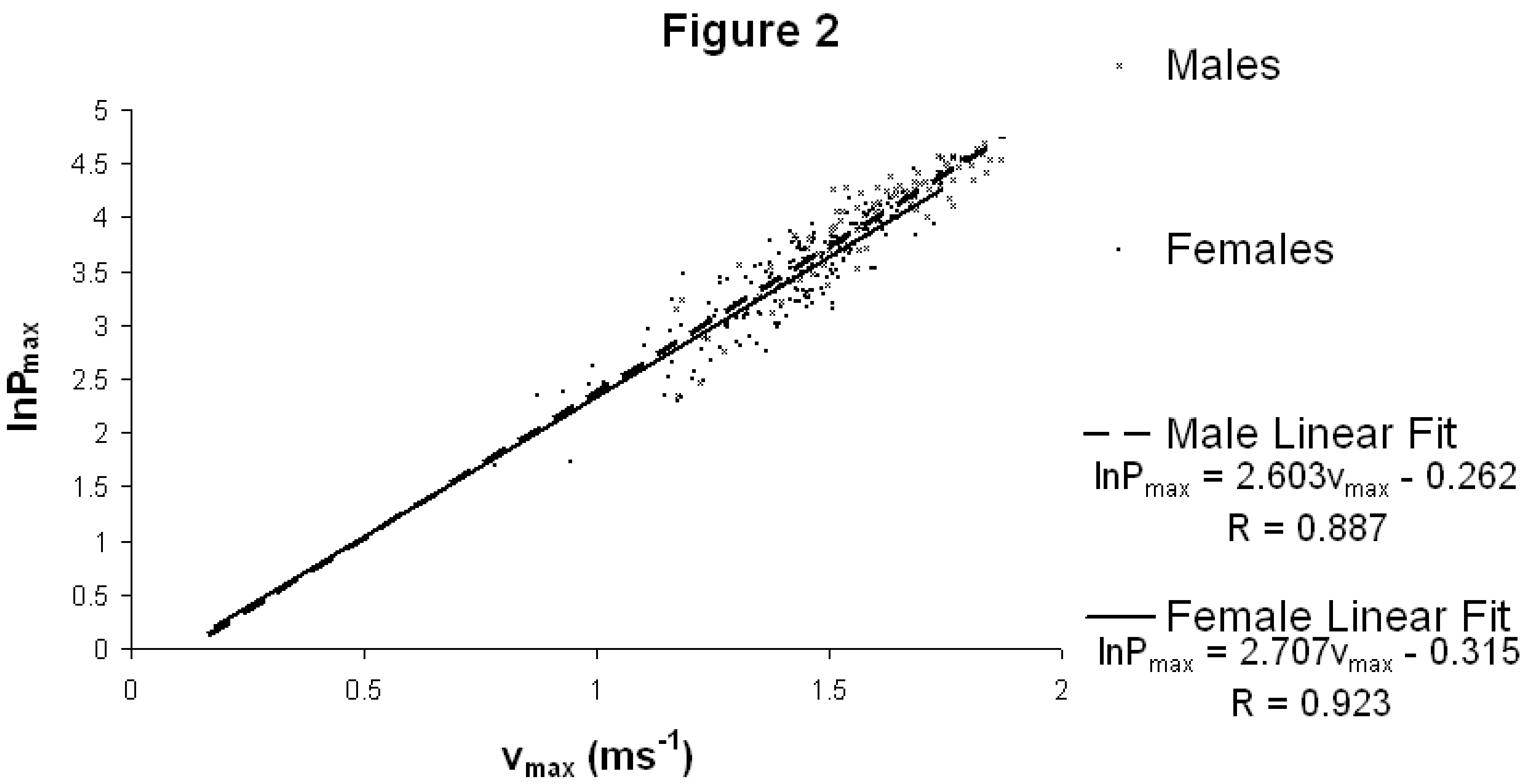


FIGURE 2 - A comparison of males vs. females. A natural log transformation of P_{max} shows both linearity and a similarity of slope acceptable for analysis with ANCOVA with v_{max} as the covariate.

Max Power and Max Velocity in the Competitive Swimming Strokes and Dolphin Kicking

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Running Title: Max Power and Max Velocity in Swimming

ABSTRACT

Purpose: The purpose of this study was to examine differences in the relationship between the maximum power delivered to an external load (P_{max}) and the maximum velocity (v_{max}) of swimming among the four competitive strokes and underwater dolphin kicking. **Methods:** 192 female and 135 male competitive swimmers of varied age, swimming experience, and swimming ability completed tests to determine v_{max} and P_{max}. The relationship was linearized using a plot of the natural log of P_{max} vs. v_{max} and comparison was made using both ANCOVA, with v_{max} as the covariate, and t-tests of slope where appropriate. **Results:** The similar slopes of the linear regressions between $\ln(P_{max})$ and v_{max} for the four competitive swimming strokes was judged appropriate for use with ANCOVA. A significant main effect ($p < 0.05$) for stroke allowed comparison of the adjusted means at $v_{max} = 1.463\ ms^{-1}$ which showed significant differences between breaststroke (88.2 W) and all other strokes, front crawl (36.1 W) and all other strokes, and no difference between butterfly (49.2 W) and backstroke (47.4 W). The slope of the linear regression between $\ln(P_{max})$ and v_{max} for underwater dolphin kick (1.354 ± 0.418) was found to be significantly different than the slope used in the ANCOVA (2.482 ± 0.070) using a t-test ($p < 0.01$). **Conclusions:** P_{max} values of the four competitive strokes have similar exponential relationships with v_{max}. Comparisons show that for the same v_{max}, the strokes rank as breaststroke, butterfly, backstroke, and front crawl from highest to lowest generated P_{max}. The relationship between P_{max} and v_{max} for underwater dolphin kick is considerably different from that of the four competitive strokes both in the strength of the relationship and the exponential coefficient. **Key Words:** RESISTED SWIMMING, TETHERED SWIMMING, ACTIVE DRAG, SPRINT SWIMMING

INTRODUCTION

Swimming against an external resisting force such as a tether is one of the most available and often studied areas of swimming related research. In 1912, Houssay (8) examined the concept of power delivered to an external load (P_{load}) and identified the presence of a local maxima (P_{max}). Recently, the relationship of P_{max} to the maximum swimming velocity (v_{max}) of a swimmer has been found to be appropriately modeled by an exponential fit for front crawl (19). P_{max} values have only been determined for front crawl (3, 4, 10, 17, 18, 19) and breaststroke (5). While the relationship between P_{max} and v_{max} has been examined for front crawl (10, 17, 18, 19), it has not been studied in any of the other modern competitive strokes or underwater dolphin kick. Underwater dolphin kick is of interest in addition to the competitive strokes as it may comprise up to 60% of a butterfly, backstroke, or freestyle event.

Differences among competitive strokes have been observed in the maximum force (F_{max}) that a swimmer can generate against a tether at zero velocity. Breaststroke tends to generate greater force than the other three strokes (12, 13, 14). Strong linear correlations have also been observed between F_{max} and v_{max} or performance measures such as best competitive sprint performance in backstroke(9) and front crawl (2, 6, 9, 15, 21). These findings indicate that differences in P_{max} and the P_{max} vs. v_{max} relationship may exist among the four competitive strokes and underwater dolphin kick. The purpose of this study was to compare the P_{max} vs. v_{max} relationships of the four competitive strokes and underwater dolphin kick. The P_{max} vs. v_{max} relationship is of particular interest as it appears to be related to the propulsive and active drag forces acting on swimmers. Exploration of the relationship may cast light onto both the way in which the relationship is related to the propulsive and active drag forces and the differences in these forces among the competitive strokes and underwater dolphin kick.

METHODS

Subjects. A total of 327 competitive swimmers of a variety of ages and abilities from the Midwest United States participated in the study. The study was approved by the Indiana University Human Subjects Committee and written informed consent was obtained from each subject and a parent or guardian if the subject was a minor. The age, height, and body mass of each subject was obtained in order to describe the subject population (Table 1).

Procedure.

v_{max}. The maximum swimming velocity (v_{max}) of the subject was determined over 13.72 m. Each subject completed two 22.86 m swims at maximal effort. In order to remove the effect of the wall push off and finish on the velocity, the first and last 4.57 m were not timed. The time required for the head of the swimmer to complete the middle 13.72 m of the each swim was measured by hand timing with a stopwatch and velocity was calculated using the known distance and time. The average velocity of the two swims was used as v_{max}.

P_{load}. The power delivered to an external load (P_{load}) was measured from a series of 10 m maximal effort swims with the subject attached via a waist belt to a weight and pulley system. Each subject completed 15 m swims at maximal effort against a variety of external loads. In order to remove the effect of the wall push off, the first 3.45 m of the swim were not timed. The time required for the head of the swimmer to complete the next 10 m of the each swim was measured by hand timing with a stopwatch and velocity was calculated using the known distance and time. The external load was applied via a modified Power Rack (a weight and pulley system from Total Performance Inc. modified by Jerden Industries). The average force at different plate settings was calibrated over the 10 m measurement zone using a force transducer. P_{load} was calculated as the product of the force of the external load and the velocity of the swimmer.

P_{max}. A plot of external resistive load vs. the velocity attained at this load during maximal effort is commonly accepted to be linear for an individual swimmer (1, 3, 16, 17). It follows then, that the P_{load} vs. velocity curve is parabolic for each subject. P_{load} was measured for progressively increasing loads until a peak was observed. P_{max} was defined as the largest measured P_{load}.

Statistical Analysis. Statistical analysis was used to compare the measured values of P_{max} and v_{max} and the relationship between P_{max} and v_{max} among the four competitive strokes and underwater dolphin kick. A one-way independent groups ANOVA was used to ascertain differences in both P_{max} and v_{max} with pairwise comparisons made using a

Bonferonni adjustment to maintain experiment wide error at $\alpha = 0.05$. Differences among the strokes' relationships between P_{max} and v_{max} were analyzed in two ways. In both cases, the relationship was first linearized by use of the natural log of P_{max}. If the slopes of the treatment conditions were similar, as indicated by a non-significant interaction of slope and stroke, then the differences were calculated using ANCOVA. Post-hoc analysis of differences was completed using a Bonferonni adjustment to maintain experiment wide error at $\alpha = 0.05$. If the slopes of the treatment conditions were different, the slopes were compared using a t-test $\alpha = 0.01$ (20).

RESULTS

Mean values for v_{max} and P_{max} for each of the four competitive strokes and underwater dolphin kicking are presented in Table 2. Analysis using an ANOVA ($p < 0.05$) and post-hoc analysis completed with a Bonferonni adjustment showed a significant main effect of stroke for v_{max} with differences only between breaststroke and the other treatments and no significant main effect of stroke for P_{max}. The relationships between v_{max} and P_{max} were analyzed by first linearizing the data using a natural logarithmic transformation of P_{max}. ANCOVA analysis of $\ln(P_{max})$, with v_{max} as the covariate, was not appropriate for use with all five treatment conditions as indicated by a significant interaction ($p < 0.05$) between the slope of the line and the treatment condition. As dolphin kick was noticeably different from the four competitive strokes, it was removed and the analysis was rerun. ANCOVA was appropriate for use with the four competitive strokes as the interaction between the slope and the treatment condition was not significant. The ANCOVA with the four competitive strokes showed a significant main effect for stroke ($p < 0.05$). Post-hoc analysis for pairwise differences in $\ln(P_{max})$ using a Bonferroni adjustment to maintain experiment wide error rate at $\alpha = 0.05$ showed significant differences between breaststroke and each of the other strokes, front crawl and each of the other strokes, and no difference between backstroke and butterfly (Table 3). Table 4 shows both the percentage differences in $\ln(P_{max})$ and the percentage differences reconverted to P_{max} (correcting for the difference between the geometric mean of the logarithmic scale and the arithmetic mean of the normal scale using the consistent estimator I (7)) between the strokes at $v_{max} = 1.463\ ms^{-1}$. Percentage differences in $\ln(P_{max})$ should be interpreted with care as prediction from regression using a logarithmic scale can be biased by non-logarithmic residual variance around the regression. For the purposes of the current study, the combination of small residuals and similar residual variance for each of the different treatments makes this less of a concern. Underwater dolphin kicking showed the worst correlation to $\ln(P_{max})$ and also showed a significant difference ($p < 0.01$) in slope from that used in ANCOVA of the four competitive strokes (1.354 ± 0.418 vs. 2.482 ± 0.070).

DISCUSSION

The purpose of the study was to compare the relationship between P_{max} and v_{max} in the four competitive strokes and underwater dolphin kick (5 treatments). In order to examine this relationship, swimmers with a wide range of v_{max} values were used. This leads to a large standard deviation in both v_{max} and P_{max} and appropriately a general of lack of significant differences between treatment conditions in either of these two variables. The exception to this was the significant differences seen in the v_{max} of breaststroke from the other treatment conditions. As the slowest of all strokes, it was not possible to obtain a subject population with v_{max} values in the range of the other four treatments while maintaining a large distribution in values of v_{max}.

In order to examine differences in the relationship between P_{max} and v_{max}, two assumptions were made based upon the more thorough investigation done for front crawl (19): appropriateness of an exponential fit and lack of a practically important difference between sexes. Analysis of the relationship between P_{max} and v_{max} for front crawl showed that an exponential fit was a more appropriate model than a linear fit (19). It was assumed that this concept would also hold true for the other competitive strokes and dolphin kick. The large and significant linear correlations found between $\ln(P_{max})$ and v_{max} for the other three competitive strokes and dolphin kick ($R = 0.93, 0.92, 0.88, 0.70$ for butterfly, backstroke, breaststroke and dolphin kick respectively) confirm that the exponential model is appropriate.

Despite the statistically significant differences found between males and females for front crawl (19) subject populations of males and females were analyzed together during this study. The rational was to increase the v_{max} range in the available subject population while still maintaining the criteria of testing experienced competitive swimmers. The statistically significant differences between the sexes can be ignored based on the large subject number and associated high power of the analysis if these differences are not large enough to confound the desired variables (the differences between the competitive strokes). If the differences between the competitive strokes are considerably larger than the differences between the sexes, then sex can be ignored as a confounding variable. The similarity of the v_{max} used for the adjusted means of the ANCOVA analysis for sex in front crawl (1.476 ms^{-1}) (19) and of the four competitive strokes (1.463 ms^{-1}) allows for an easy comparison of effect sizes. While sex can cause a maximum difference in the mean of P_{max} of approximately 10% (19), the significant differences found between the competitive strokes range from 23.7% to 59.5%. Thus, it is impossible for these differences to have been caused by sex as a confounding variable. It is possible, but unlikely, that practically important and statistically significant differences between butterfly and backstroke could be found with single sex analysis and a large subject number. Likewise, it can be said with certainty that the difference between backstroke and butterfly is less than the difference between males and females in front crawl.

The results of the current study have interesting implications on the underlying causes of the relationship between P_{max} and v_{max} in swimming. Differences in this relationship can be caused by differences in either propulsive force, active drag force, or both. Swimming at a constant velocity can theoretically be achieved through any combination of equal and opposite propulsive and active drag forces. The propulsive force required to achieve any given velocity will vary between the competitive strokes due to the presumed differences in active drag. It is possible that these differences are elucidated by the differences observed in the P_{max} to v_{max} relationship.

The differences found between the competitive strokes shows a striking similarity of pattern to the average active drag force differences between strokes computed using the velocity perturbation method (11). Table 5 presents the percentage differences in active drag force between the four competitive strokes at $v_{max} = 1.45$ ms^{-1} in males found using the velocity perturbation method (11) and the percentage differences in P_{max} at $v_{max} = 1.463$ ms^{-1} found by the present study scaled by a factor of 125%. The scaling factor was chosen in order to standardize the percentage difference between front crawl and butterfly and is appropriate as it may account for an unknown coefficient. The similarities between the P_{max} differences and the active drag force differences of the velocity perturbation model are further indication that the P_{max} vs. v_{max} relationship may be able to detect differences in active drag forces.

Also of interest is the marked difference of underwater dolphin kicking from the four competitive strokes. The difference in slope is logical if the relationship is considered to be indicative of active drag, as underwater dolphin kicking is akin to a passive drag condition with the arms locked in a streamline position. Also interesting is the greater variability and resulting lower correlation value of dolphin kicking. This may be an indication that while individual variation in the active drag characteristics within each of the four competitive strokes is low, variation in drag in underwater dolphin kicking is relatively large. Swimmers with larger amplitude dolphin kicks were informally observed to be those that generated larger P_{max} values in relation to v_{max}. This may indicate that a larger amplitude kick has both larger drag and larger propulsive forces than a smaller amplitude dolphin kick and is an appropriate area for further study.

Given the results of the current study, the cause of the differences between the competitive strokes is of great interest. The most logical area of further study involves examination of changes in the P_{max} vs. v_{max} relationship with independent changes in active drag and propulsive forces as well as a direct comparison with the velocity perturbation method.

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We would like to thank Jim Steen of Total Performance Inc., Bill Jerden of Jerden Industries, and Dave Tanner for help in supplying materials, constructing, testing, and calibrating the equipment used. We would also like to thank all of the subjects and the numerous data collectors that helped make the large amount of data collection possible.

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CONFLICT OF INTEREST

There is no conflict of interest to disclose for this paper.

Table 1

Stroke	Sex	N	Age (yrs)			Height (cm)			Mass (kg)		
Butterfly	M	7	16.6	±	3.7	174.1	±	9.9	70.7	±	15.7
	F	2	16.5	±	2.1	171.1	±	1.7	75.2	±	8.3
Backstroke	M	8	17.9	±	3.3	176.7	±	21.7	75.3	±	15.6
	F	4	14.0	±	3.2	162.8	±	11.4	53.7	±	14.2
Breaststroke	M	5	14.7	±	4.2	167.2	±	16.1	54.8	±	20.5
	F	4	14.7	±	3.8	167.3	±	4.6	55.6	±	11.9
Front Crawl	M	105	15.6	±	2.7	171.9	±	13.0	64.2	±	14.8
	F	178	13.9	±	2.9	160.5	±	11.3	54.6	±	13.2
Dolphin Kick	M	10	21.4	±	1.8	180.2	±	4.4	79.3	±	6.2
	F	4	23.0	±	3.7	165.9	±	6.6	64.8	±	2.4

TABLE 1 - A description of the subject population divided by stroke

Table 2

Stroke	v_{max} (ms^{-1})			P_{max} (W)		
Butterfly	1.47*	±	0.22	56.0	±	26.3
Backstroke	1.46*	±	0.18	54.0	±	29.0
Breaststroke	1.05	±	0.17	32.8	±	16.5
Front Crawl	1.48*	±	0.19	43.3	±	22.7
Dolphin Kick	1.46*	±	0.19	40.0	±	15.5

* significantly different than breaststroke $p < 0.05$

TABLE 2 - Mean ± standard deviation of maximum swimming velocity (v_{max}) and maximum power delivered to an external load (P_{max}). Differences in v_{max} detected by post-hoc pairwise of a significant ANOVA with a bonferonni adjustment. ANOVA analysis of the P_{max} was not significant.

Table 3

Stroke	$\ln(P_{max})$	P_{max} (W)
Butterfly	3.895*+	50.0
Backstroke	3.858*+	48.5
Breaststroke	4.480+	91.4
Front Crawl	3.585*	37.0

* significantly different than breaststroke $p < 0.05$

\+ significantly different than front crawl $p < 0.05$

TABLE 3 - Maximum velocity adjusted means (compared at $v_{max} = 1.463\ ms^{-1}$) for the natural log of maximum power delivered to an external load ($\ln(P_{max})$) and the means converted back to P_{max} (7). Significant differences determined by bonferonni adjusted pairwise comparisons of a significant ANCOVA.

Table 4

Stroke	Butterfly	Backstroke	Breaststroke	Front Crawl
Butterfly		0.0	13.0	8.0
Backstroke	3.0		13.8	7.1
Breaststroke	45.3	46.9		20.0
Front Crawl	26.0	23.7	59.5	

TABLE 4 - Percentage differences in maximum velocity adjusted means (compared at v_{max} = 1.463 ms^{-1}) for the natural log of maximum power delivered to an external load ($ln(P_{max})$), top and right, and the means converted back to P_{max} (7), bottom and left.

Table 5

Stroke	Butterfly	Backstroke	Breaststroke	Front Crawl
Butterfly		2.1	53.8	33.2
Backstroke	3.8		54.8	31.8
Breaststroke	56.6	58.6		79.1
Front Crawl	32.5	29.6	74.4	

TABLE 4 - Percentage differences in the active drag forces of males with maximum velocity (v_{max}) = 1.45 ms^{-1} from the velocity perturbation method (11), top and right, and maximum velocity adjusted means (compared at v_{max} = 1.463 ms^{-1}) for maximum power delivered to an external load (P_{max}) scaled by a factor of 125%, bottom and left.

Figure 1

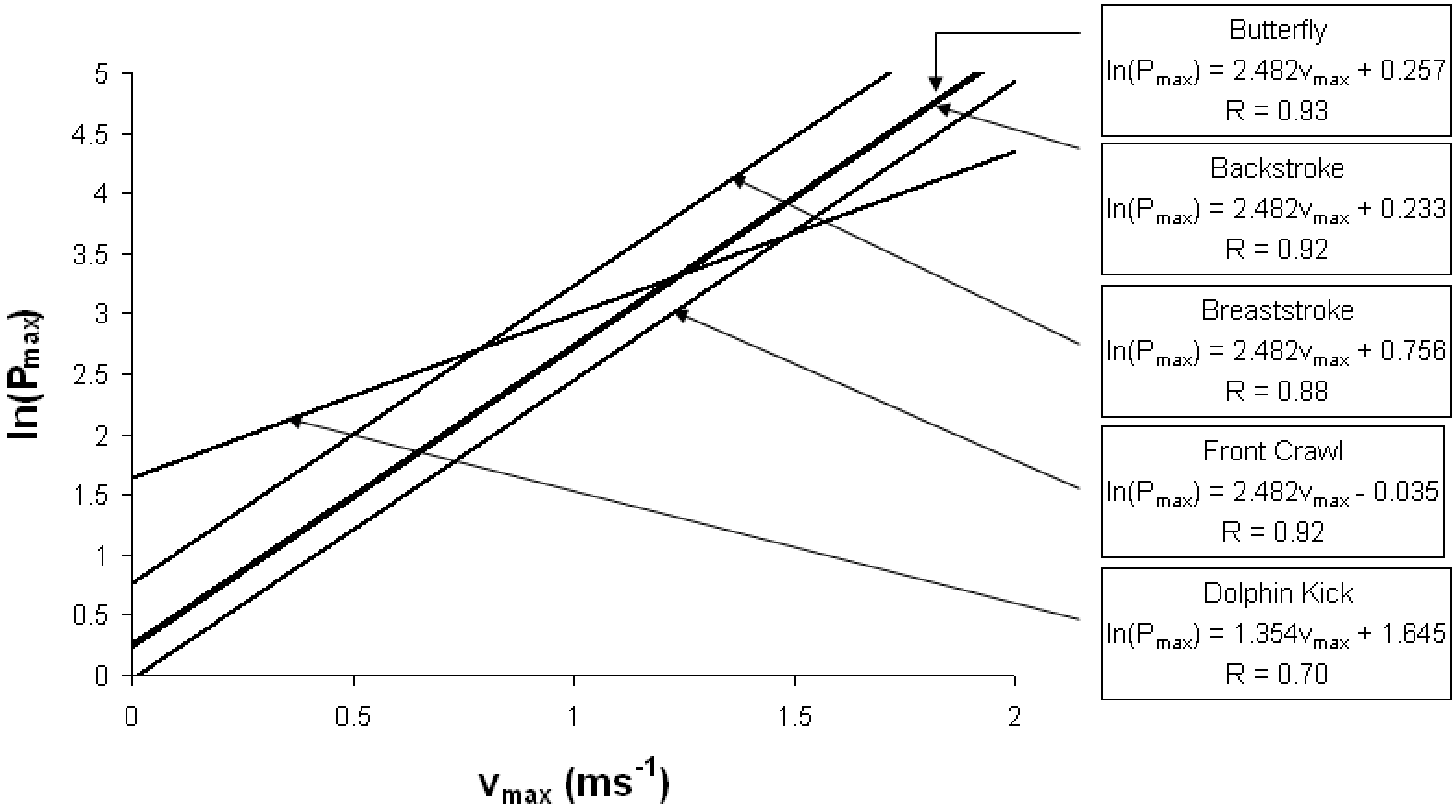

FIGURE 1 - ANCOVA adjusted slope best fit lines for the four competitive strokes show a significantly different ($p < 0.01$) slope than underwater dolphin kicking.

Drag and Propulsive Force Modification in the Max Power and Velocity Perturbation Models

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Running Title: F_{ad} and F_{prop} detection with the MPM and VPM

ABSTRACT

Purpose: The purpose of this study was to evaluate the validity of the Velocity Perturbation Method (VPM) and the Max Power Model (MPM; a new method involving the relationship between the maximum power delivered to an external load (P_{max}) and maximum velocity (v_{max})) based on the ability to detect and separate experimentally applied independent differences in active drag (F_{ad}) and propulsive (F_{prop}) forces during swimming. **Methods:** 10 male competitive swimmers of varied experience and ability completed tests to determine v_{max} and P_{max} for use with the MPM and F_{ad} and the active drag coefficient (k) using the VPM. In addition to standard front crawl, attempts were made to independently increase and decrease F_{ad} using a pocketed drag suit and a wetsuit respectively and increase and decrease F_{prop} using hand paddles and fist gloves. v_{max}, P_{max}, k, and $F_{ad(VPM)}$ were compared across the treatment conditions by use of repeated measures ANOVA. The relationships between P_{max} and v_{max} were linearized using the natural log of P_{max} vs. v_{max} and comparison of the treatment conditions was made using repeated measures ANCOVA, with v_{max} as the covariate. **Results:** In comparison to standard front crawl, both P_{max} and v_{max} were found to be significantly increased ($p < 0.05$) over the standard condition by the wetsuit and the paddles and significantly decreased ($p < 0.05$) by the pocketed drag suit and fist gloves. No differences were seen in k between treatment conditions and differences in $F_{ad(VPM)}$ were seen only between the standard and paddles treatments. Planned comparisons showed that the relationship between P_{max} and v_{max} was significantly different from the standard condition for the glove and wetsuit treatments ($p < 0.05$), but not for the dragsuit or paddles. Finally, the

F_{ad} of the VPM and P_{max} show a significant linear correlation ($R = 0.83$). **Conclusions:** While the VPM and P_{max} are measuring the same concept, neither the VPM nor the relationship between P_{max} and v_{max} were able to appropriately separate the attempted independent modifications of F_{ad} and F_{prop}. Nevertheless, while still needing further validation the MPM shows promise as a method of detecting, separating, and quantifying differences in F_{ad} and F_{prop}. **Key Words:** TETHERED SWIMMING, ACTIVE DRAG, PROPULSION, SPRINT SWIMMING

INTRODUCTION

The measurement of active drag forces (F_{ad}) and propulsive forces (F_{prop}) during swimming has been one of the most difficult and yet essential processes in swimming research to date. One of the inherent difficulties in doing so is that at a constant velocity F_{ad} and F_{prop} are equal and opposite. Many current methods are limited by either time and cost, an ability to measure only a very limited range of swimming motions, or complexity. The most readily accessible methods of assessing F_{ad} and F_{prop} are those involving changes to swimming velocity with the addition of external resistance (3, 4, 8, 12, 13, 14, 15, 18, 19, 20). Unfortunately these methods tend to be the least face valid as they are based on untested assumptions. Furthermore, work to validate the methods is rare.

The most well developed of these methods is the velocity perturbation method (VPM) of Kolmogorov and Duplishcheva (9). The VPM purports to measure F_{ad} for swimmers at v_{max}. The VPM has been used to evaluate F_{ad} for the four competitive strokes in a large number of swimmers of dramatically different age and ability levels (9, 10) as well as F_{ad} for fin swimmers (2). Furthermore the validity of the VPM and its assumptions have been tested with varying levels of success by several different methods (11, 16, 21, 23).

Previous research in our lab (24, 25) has led us to suggest that the relationship between the maximum power delivered to an external load (P_{max}) and the maximum velocity (v_{max}) of a swimmer could be an indication of F_{ad}. This idea gives rise to the introduction and definition of the Max Power Model (MPM). The MPM hypothesizes that changes in F_{prop} will alter both P_{max} and v_{max}, but not the relationship between the two while changes in F_{ad} will not only alter P_{max} and v_{max}, but also the relationship between them. Theoretically, increases in F_{prop} will increase P_{max} and v_{max}, while decreases F_{prop} will decrease both P_{max} and v_{max}. Increases in F_{ad} will decrease P_{max} and v_{max} and increase the ratio of P_{max} to v_{max}. Correspondingly, decreases in F_{ad} will increase P_{max} and v_{max} and decrease the ratio of P_{max} to v_{max}. While the MPM is not capable of calculating values for F_{ad} or F_{prop}, it may be able to detect, separate, and quantify differences in these two forces.

The primary purpose of this study was to evaluate the validity of both the VPM and MPM based on the ability to detect and separate experimentally applied differences in F_{ad} and F_{prop}. The secondary purpose was to compare the VPM and the MPM.

METHODS

Subjects. 10 male competitive swimmers (age = 24.4 ± 3.0 yr, mass = 77.7 ± 15.3 kg, height = 181.1 ± 8.3 cm) of a variety of abilities participated in the study. The study was approved by the Indiana University Human Subjects Committee and written informed consent was obtained from each subject.

Procedure.

v_{max}. The maximum front crawl swimming velocity (v_{max}) of the subject was determined over 8 m. Each subject completed a 12 m swim at maximal effort. In order to remove the effect of the wall push off on the velocity, the first 4 m was not timed. The time required for the head of the swimmer to complete the subsequent 8 m of the swim was measured using synchronized digital video cameras and velocity was calculated using the known distance and time.

P_{load}. The power delivered to an external load (P_{load}) was measured from a series of 3 second maximal effort swims with the subject attached via a waist belt to a weight and pulley system. The external load was applied via a modified Power Rack (a weight and pulley system from Total Performance Inc. modified with the help of the Indiana University Physical Plant). The average force at different plate settings was calibrated over the measurement zone using a force transducer. Each subject completed a series of 6 to 8 sec swims at maximal effort against a variety of external loads. In order to remove the effect of the wall push off, the first 2 sec were removed. The average velocity of the swimmer over the next 3 sec was calculated by computing the travel distance of the weight stack during this time using Simi Motion Analysis Software and converting the distance to that of the swimmer using the known mechanical advantage of the weight and pulley system. P_{load} was calculated as the product of the force of the external load and the velocity of the swimmer.

P_{max}. The external load vs. velocity curve is commonly accepted to be linear for each swimmer (1, 5, 10, 14). It follows then, that the P_{load} vs. velocity curve is parabolic for each subject. P_{load} was measured for progressively increasing loads until a peak was observed. P_{max} was defined as the largest measured P_{load}.

Treatment Conditions. Each subject was given 5 treatment conditions in a randomized order over three days of testing. All treatments involved front crawl swimming. The treatments were standard front crawl, fist gloves, hand paddles, pocketed drag suit, and wetsuit. The Swim Fist Training Gloves from Kiefer were intended to decrease propulsive force by decreasing the surface area of the hands without affecting active drag force. Medium size TYR Catalyst Brite hand paddles were intended to increase propulsive force by increasing the surface area of the hands without affecting active drag force. Pocketed Drag Suits from Keifer were intended to increase the active drag force (17) without affecting the propulsive force capabilities of the swimmer. The Xterra Ventilator sleeveless triathlon wetsuits were intended to decrease the active drag force (22) without affecting the propulsive force capabilities of the swimmer.

Statistical Analysis. Statistical analysis was used to compare the measured values of k and F_{ad} (from the VPM), P_{max}, v_{max} and the relationship between P_{max} and v_{max} between the standard condition and the each of the other four treatment conditions. The planned comparisons for k, $F_{ad(VPM)}$, P_{max}, and v_{max} were analyzed using paired t-tests with $\alpha = 0.05$. Differences in the relationships between P_{max} and v_{max} were analyzed by first linearizing the relationship by use of the natural log of P_{max}. The planned comparisons between standard front crawl and each of the other four treatment conditions were analyzed using a repeated measures ANCOVA with v_{max} as the covariate, $\alpha = 0.05$. The relationship between the F_{ad} of the VPM and P_{max} was calculated by linear regression for standard front crawl and for all of the groups pooled together. Finally, the relationship between k of the VPM and the difference between the actual and predicted $\ln(P_{max})$ for standard front crawl was examined by use of a linear regression.

RESULTS

Mean values for v_{max}, P_{max}, and k from the VPM are presented in Table 1. Use of multiple t-tests as a means of assessing planned comparisons for a repeated measures design showed significant differences between each of the equipment treatment conditions and the standard conditions for v_{max} and P_{max} ($p < 0.05$). A similar analysis showed no significant differences in k and significant differences ($p < 0.05$) in $F_{ad(VPM)}$ only between the standard and paddles treatments.

In order to facilitate analysis, the relationships between P_{max} were linearized by use of the natural logarithm of P_{max}. This transformation lead to significant ($p < 0.05$) linear relationships for each of the treatment conditions (R = 0.95, 0.95, 0.98, 0.96, and 0.87 for the standard, paddles, wetsuit, dragsuit, and gloves conditions respectively).

Differences among the treatment conditions in the relationships between P_{max} and v_{max} were analyzed by a series of one-way repeated measures ANCOVA's of $\ln(P_{max})$ with v_{max} as the covariate. As the comparisons were planned, the standard condition was independently compared to each of the equipment conditions. Means for each treatment are presented in Table 2. The wetsuit and gloves treatments showed significant differences ($p < 0.05$), while the paddles and dragsuit treatments did not.

The VPM and MPM were compared in two ways. First, F_{ad} obtained using the VPM showed a significant ($p < 0.05$) linear correlation of $R = 0.83$ to P_{max} of the MPM for the standard condition. Similarly for a pooled group of all treatment conditions, the correlation between F_{ad} and P_{max} was $R = 0.75$ ($p < 0.05$). Second, k of the VPM showed a non-significant linear correlation of 0.40 to the difference between the actual and predicted $\ln(P_{max})$ values in the standard condition. This indicates that the detection of differences between individual is not the same for the VPM and MPM.

DISCUSSION

The primary purpose of this study was to evaluate the validity of both the VPM and MPM based on the ability to detect and separate experimentally applied differences in F_{ad} and F_{prop}. As an initial critique, the obtained data can be compared with existing literature. The decrease in velocity caused by the fist gloves matches well with a similar study by Craig (6) as both find that the v_{max} of swimmers wearing gloves that restrict their hand to a fist is approximately 91% of standard v_{max}. Comparison of the values of F_{ad} obtained during the present study with those in the literature is particularly important as the protocol was somewhat different. While the underlying theory and calculations of the VPM were unaltered, the duration of effort for the measurements was considerably shortened to create consistency with MPM testing protocols. As can be seen in Figure 1, the values for F_{ad} found using the VPM in the present study are comparable in both value and variability to those in the literature (9, 10).

In evaluating the response of the MPM to the treatment conditions, the results are mixed. The simple hypotheses of the MPM were upheld. As hypothesized, both P_{max} and v_{max} were significantly increased by the wetsuit and paddles and significantly decreased by the dragsuit and gloves.

The more complex hypotheses showed less certain results. It was expected based upon the MPM that the wetsuit and dragsuit conditions would cause changes in the P_{max} vs. v_{max} relationship reflecting changes in F_{ad} while the paddles and gloves would not. The experimental results did not directly bear out the hypothesized results. Significant changes in the relationship between P_{max} and v_{max} were found for the wetsuit but not the dragsuit. Despite this finding, there are two factors that continue to point to the viability of the MPM. First, while significant changes in the relationship of P_{max} to v_{max} were not seen for the dragsuit, the percent change of the mean of $\ln(P_{max})$ with v_{max} controlled was by far the largest of any of the conditions. A possible explanation for this finding is a largely varied individual response to the dragsuit causing an increase in error and thus a decrease in the power of the statistical analysis. Second, both the P_{max} v_{max} relationship changes were in the hypothesized direction. The wetsuit was the only treatment to decrease the v_{max} adjusted mean $\ln(P_{max})$ and the dragsuit exhibited the largest increase in the v_{max} adjusted mean $\ln(P_{max})$ of any treatment.

Similarly, the intended independent changes in F_{prop} did not fit the expectation of the MPM that the relationship between P_{max} and v_{max} would be unchanged. While the paddles did not cause a significant change in the relationship, the gloves caused a significant increase in $\ln(P_{max})$ with v_{max} controlled. Despite this contradiction, evidence supporting the MPM does exist. The gloves did cause a much smaller change in the relationship between P_{max} and v_{max} than the dragsuit (6.9% vs. 9.9% respectively) despite causing a larger change in v_{max} (9% vs 6% respectively).

It is possible that some of the findings contrary to the MPM are due to deviations of the treatment effects from the desired independent modification of F_{prop} and F_{ad}. For example, while the primary effect of the gloves is to decrease F_{prop}, it is also possible that the body of the subject swimming with gloves is lower in the water than the during the standard condition causing an increase in F_{ad} at that velocity. This could cause the shift in the P_{max} v_{max} curve that was observed. The treatments selected were determined to be the most appropriate, however the use of a wider variety of treatment conditions with the same purpose would allow for further interpretation. These treatments could include equipment such as fins (to alter only F_{prop}) or dragsuits with a variety of pocket sizes.

The large individual variability in response to the treatment conditions along with the difficulties in independently modifying F_{ad} and F_{prop} suggest that an independent groups design may be an appropriate choice for future experimentation. The repeated measure design was chosen in order to detect what were anticipated to be very small changes. At this it was successful and showed the ability to detect very small changes (< 1% in the case of the wetsuit). However, similar statistical power could be obtained in a future study by using a large subject number in an independent groups design which would obtain further power through the use of ANCOVA.

In evaluating the ability of the VPM to detect independent alterations in F_{prop} and F_{ad}, the most striking disadvantage is the large amount of random error inherent in the procedure. As noted, no differences in k were detected between the treatments. This large error is likely due to the prominent use and large powers of the two velocity measurements (which have the more error than the force measurements). In an attempt to increase the power of the analysis, F_{ad} was analyzed using an ANCOVA with v_{max}^2 as the covariate. The choice of the covariate was based on the assumption of the VPM that F_{ad} is proportional to velocity squared. This analysis was also unable to detect differences between the standard condition and any of the equipment treatments.

The secondary purpose of this study was to compare the VPM and the MPM. In comparing the VPM and the MPM it is obvious that the two measurements are related, but that at least one of them (and perhaps both) is incapable of detecting differences in F_{ad} between individuals. The strong linear correlation between $F_{ad(VPM)}$ and P_{max} is particularly encouraging when the large amount of random error inherent in the VPM calculations is taken into account. The VPM presumably has the ability to detect differences in F_{ad} at the level of the individual. These difference are standardized against individual differences in v_{max} by the use of the drag coefficient k. It is possible that the MPM is also capable of measuring differences at the level of the individual. The measure of the individual variability in the MPM would be determined by the displacement of the individual point from the best fit line of $\ln(P_{max})$ vs. v_{max}. Individuals displaced above and below the line would be interpreted as having larger and smaller Fad at any given velocity than average respectively. In comparing the VPM and MPM then, individuals with large k values from the VPM would be have large positive differences between $\ln(P_{max})$ and predicted $\ln(P_{max})$. Therefore if both the VPM and MPM are capable of measuring individual differences in F_{ad}, a correlation between k and actual – predicted $\ln(P_{max})$ should exist. k of the VPM showed a non-significant linear correlation of 0.40 to the difference between the actual and predicted $\ln(P_{max})$ values for standard front crawl. This indicates that the mechanisms for detecting individual differences in F_{ad} from the VPM and the MPM are not related. While one of the methods may be able to detect individual differences, both do not. It is unlikely that the VPM is capable of detecting differences in individuals due to the inherent error. In order to test the sensitivity of the MPM to individual difference, it must be compared to a more sensitive method such as the MAD system (23).

While currently in need of further validation, the MPM shows promise as a method to detect differences in F_{ad} and F_{prop}. The MPM compares favorably with the VPM and has the added advantage of a lower associated random error and therefore increased statistical power.

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CONFLICT OF INTEREST

There is no conflict of interest to disclose for this paper.

Table 1

	v_{max} (ms^{-1})			P_{max} (W)			k		
Condition	Mean	SEM	t	Mean	SEM	t	Mean	SEM	t
Standard	1.664	0.068		84.8	10.4		25.45	2.22	
Paddles	1.716	0.066	-3.158*	95.2	10.8	-5.447*	27.41	2.08	-1.27
Wetsuit	1.733	0.049	-2.902*	91.9	10.4	-5.258*	24.6	2.69	0.31
Dragsuit	1.563	0.056	4.664*	77.7	8.6	2.678*	26.65	1.81	-0.52
Gloves	1.511	0.056	5.093*	68.8	8.4	5.924*	27.8	4.98	-0.45

* Significantly different than the standard condition ($p < 0.05$)

TABLE 1 - Mean, standard error, and t value evaluating the difference of each treatment condition from the standard for v_{max} (maximum swimming velocity), P_{max} (maximum power delivered to an external load), the coefficient of drag from the VPM (k).

Table 2

			$\ln(P_{max})$	P_{max} (W)	
	Treatment	v_{max} (ms^{-1})	Mean	Mean	% diff
Paddles	Standard	1.69	4.417	84.8	
	Paddles	1.69	4.453	88.0	3.8
Wetsuit	Standard	1.70	4.439	86.6	
	Wetsuit	1.70	4.396*	81.4	-6.0
Dragsuit	Standard	1.61	4.279	74.1	
	Dragsuit	1.61	4.388	81.4	9.9
Gloves	Standard	1.59	4.233	70.9	
	Gloves	1.59	4.302*	75.8	6.9

* Significantly different than the corresponding standard condition ($p < 0.05$)

TABLE 2 - Means for the natural logarithmic transformation of the maximum power delivered to an external load ($\ln(P_{max})$) and the reconversion of these means into P_{max} (correcting for the difference between the geometric mean of the logarithmic scale and the arithmetic mean of the normal scale using the consistent estimator I (7)) along with the maximum velocity (v_{max}) at which these means were calculated and the percentage change of the equipment treatment from the standard.

CHAPTER 5: DISCUSSION

Introduction

This final chapter will cover three topics. First, each research question will be answered explicitly and any deviation of results from the hypothesis will be explained. This section will be organized under the same sub-study categories as in the first chapter and the manuscripts. Second, the validity and usefulness of the Max Power Model (MPM) will be evaluated based upon the results of the study. Finally suggestions for future study will be made.

Evaluation of research questions

Determination of the shape of the relationship between P_{max} and v_{max} for front crawl and development of a method of comparing P_{max} vs. v_{max} curves

Question: What function (of linear, power, and exponential) best describes the relationship between the maximum power delivered to an external load (P_{max}) and the maximum free swimming velocity (v_{max}) during front crawl swimming?

Hypothesis: A power function will best describe the relationship between P_{max} and v_{max} during front crawl swimming.

Analysis: The best function to describe the relationship between P_{max} and v_{max} was determined by a comparison of the R values for the correlations using a series of t-tests developed by Hotelling (1940).

Answer: The linear correlation (R = 0.879) was significantly smaller ($p < 0.01$) than both the power (R = 0.926) and exponential correlations (R = 0.927) which did not differ from one another. Furthermore, the linear correlation had an intercept significantly ($p < 0.01$) different than the theoretical intercept of the origin. A power function was hypothesized to be the best fit based upon the expected dependence of the P_{max} v_{max} curve on resistive forces (F_{res}). F_{res} is thought to be proportional to v^2 and it was thus anticipated that P_{max} would likely be proportional to v^3. The exponential fit also allows for greater ease in the analysis of differences in the P_{max} vs. v_{max} relationship. Based on these two criteria, the exponential function was used throughout the rest of the analytical procedures.

Question: What statistical method can be used to test for differences in the relationships of P_{max} vs. v_{max} between different treatments, swimming styles, and anthropometric qualities?

Hypothesis: A transformation of v_{max} based upon the power function will allow linearization of the relationship between P_{max} and v_{max}. Comparison of the P_{max} v_{max} relationship between treatments, swimming styles, and anthropometric qualities can then be accomplished using ANCOVA with the transformed v_{max} variable as the covariate.

Analysis: As this question involves the development of an analytical procedure, the analysis used is more appropriately described as a result of the study.

Answer: Based upon the findings for the first research question and deviating from the hypothesis, the P_{max} v_{max} relationship was linearized by taking the natural logarithm of P_{max}. The analysis was then continued in two ways. If the slopes of $\ln(P_{max})$ vs. v_{max} of the groups to be compared were sufficiently similar for use with ANCOVA with v_{max} as the covariate (as judged by a non-significant ($p > 0.05$) interaction between slope and group), then ANCOVA was used to detect differences between groups. If the slopes were not sufficiently similar for use with ANCOVA (as judged by a significant ($p < 0.05$) interaction between slope and group), then the slopes were tested for differences using a t-test (Wright, 1978). The second portion of the analytical procedure involving the comparison of slopes was not anticipated to be necessary and thus was not included in the hypothesis. The addition of this analytical procedure was added after the second part of the study contained groups (underwater dolphin kick in comparison to all of the competitive strokes) without sufficiently similar slopes for ANCOVA.

Evaluation of the relationship of P_{max} vs. v_{max} for the four competitive strokes and underwater dolphin kick

Question: Does the relationship between P_{max} and v_{max} differ for the four competitive strokes and underwater dolphin kick?

Hypothesis: The relationship between P_{max} and v_{max} will differ for the four competitive strokes and underwater dolphin kick. Breaststroke will have the greatest ratio of P_{max} to v_{max} and underwater dolphin kick will have the smallest ratio of P_{max} to v_{max} with the other three strokes falling in between.

Analysis: The relationships between P_{max} and v_{max} were compared based on the procedure developed in the first sub-study. All pairwise comparisons in the ANCOVA were made post-hoc using a bonferonni adjustment to maintain the experiment wide error rate at $\alpha = 0.05$.

Answer: The relationship between P_{max} and v_{max} does differ for the four competitive strokes and underwater dolphin kick. The four competitive strokes had similar slopes for $\ln(P_{max})$ vs. v_{max} and were thus analyzed by use of ANCOVA. As hypothesized, breaststroke showed a significantly larger $\ln(P_{max})$ value at the v_{max} adjusted mean than any of the other strokes. Continuing beyond the hypothesis, front crawl showed a significantly smaller $\ln(P_{max})$ value at the v_{max} adjusted mean than any of the other strokes and backstroke and butterfly were not statistically different. Deviating from the hypothesis, underwater dolphin kick was not able to be analyzed using ANCOVA due to a significant difference in slope for $\ln(P_{max})$ vs. v_{max} from the combined data of the competitive strokes. As the lines cross, it is incorrect to say that underwater dolphin kick has a smaller ratio of P_{max} to v_{max}. Examining Manuscript 2 Figure 1 (reproduced below), it can be seen that the best fit line for underwater dolphin kick intercepts breaststroke at ~ 0.75 ms^{-1}, butterfly and backstroke at ~ 1.3 ms^{-1}, and finally front crawl at ~ 1.5 ms^{-1}. After these v_{max} values, the ratio of P_{max} to v_{max} for underwater dolphin kick is indeed lower than the respective strokes. The difference in slope of underwater dolphin kick from the competitive strokes is one of the most interesting findings of the study. It implies that the exponential growth of P_{max} with increases in v_{max} is slower for underwater dolphin kicking than for the competitive strokes (for which the exponential growth rate is quite similar). Viewed in the context of the MPM this would indicate a fundamental difference in the relationship between F_{res} and velocity for underwater dolphin kick in relation to the competitive strokes. Contextually, this finding is not surprising as dolphin kicking is similar to a condition where F_{res} is passive drag (because the arms are not in motion) while for the competitive strokes F_{res} is active drag. The validity and usefulness of the MPM is bolstered by this finding as the MPM is appropriately interpreting the experimental findings.

Manuscript 2 Figure 1

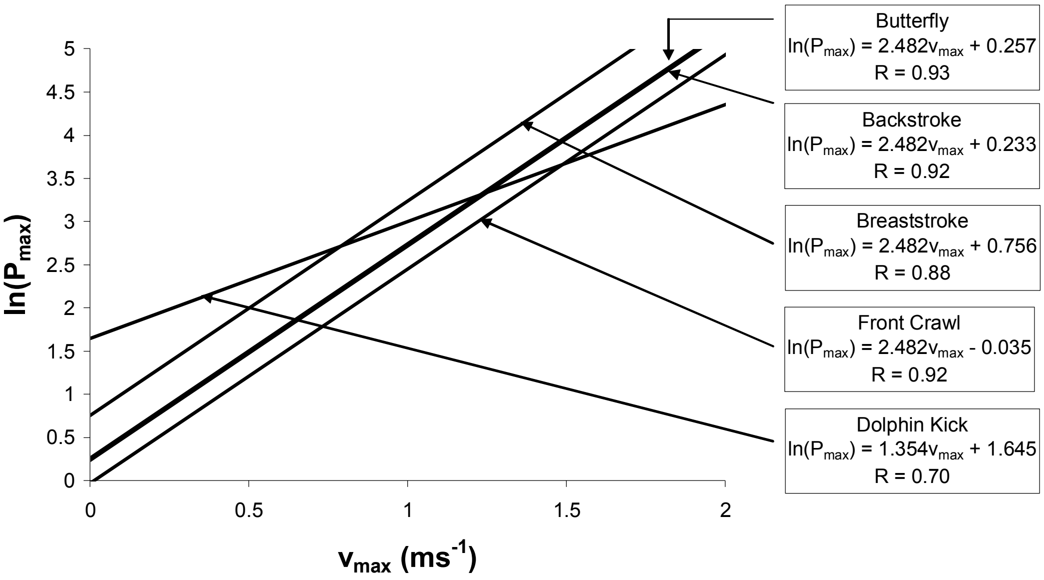

FIGURE 1 - ANCOVA adjusted slope best fit lines for the four competitive strokes show a significantly different ($p < 0.01$) slope than underwater dolphin kicking.

Examination of the validity of the Max Power Model using independent modification of the resistive and propulsive forces and comparison with the Velocity Perturbation Model

Question: Does the P_{max} vs. v_{max} relationship differ between standard front crawl swimming and 4 equipment treatment conditions during front crawl swimming: hand paddles, fist gloves, a pocketed drag suit, and a wet suit?

Hypothesis: Normal swimming and the use of hand paddles and fist gloves will all result in the same relationship between P_{max} and v_{max}, however paddles increase both the P_{max} and v_{max} of an individual and fist gloves decrease both of the variables. Normal swimming has a different relationship between P_{max} and v_{max} than does the use of a pocketed drag suit or wearing a wet suit. When compared to normal front crawl swimming, the use of a pocketed drag suit decreases both P_{max} and v_{max} and also increases P_{max} relative to v_{max}. When compared to normal front crawl swimming, wearing a wet suit increases both P_{max} and v_{max} and also decreases P_{max} relative to v_{max}.

Analysis: Differences in P_{max} and v_{max} were analyzed using planned comparisons for a repeated measures ANOVA. These planned comparisons take the form of paired t-tests (Keppel & Wickens, 2004) $\alpha = 0.05$. The relationships between P_{max} and v_{max} were compared based on the procedure developed in the first sub-study. Planned comparisons in the form of ANCOVAs $\alpha = 0.05$ with only the standard and one treatment condition were used to evaluate difference between each treatment and standard front crawl swimming.

Answer: The hypotheses for this research question were based on the predictions of the MPM. The results of the analysis for differences in P_{max} and v_{max} fit directly with the hypothesis. Both P_{max} and v_{max} were significantly increased for the paddles and wetsuit and decreased for the gloves and dragsuit.

On the other hand, differences in the P_{max} vs. v_{max} relationship did not fit with the hypothesis. These differences will be evaluated and discussed one treatment at a time beginning with the treatments that increased v_{max}. The paddles treatment fit with the hypothesis in that the P_{max} v_{max} relationship was not different from the standard condition. As predicted by the MPM, an increase in F_{prop} with no change in F_{res} did not lead to a change in the P_{max} v_{max} relationship but it did increase both P_{max} and F_{max}. Also fitting with the hypothesis, the P_{max} v_{max} relationship for the wetsuit was significantly different from the standard. In the context of the MPM, a decrease in F_{res} with no change in F_{prop} led to a significant change in the P_{max} v_{max} relationship from the standard condition as expected. This change was not only significant, but also in direction predicted by the

MPM with the ratio of P_{max} to v_{max} decreasing for the wetsuit in comparison with the standard condition.

Toussaint et al. (1989) examined the effect of a triathlon wetsuit on F_{res} using the Measuring Active Drag System at velocities of 1.1, 1.25, and 1.5 m/s. They found reductions in F_{res} from the standard condition while wearing the wetsuit of 16.1%, 14.2%, and 12.1% for the above velocities respectively. The present study evaluated the differences in P_{max} at $v_{max} = 1.70$ m/s and found that the wetsuit reduced P_{max} by 6.0%. The percentage differences can not be directly compared because the relation of P_{max} to F_{res} is unknown. Furthermore, the velocities used by Toussaint et al. are not v_{max} and thus the percentage differences are likely different than if the efforts were maximal, as is evidenced by the changes in F_{res} reduction with increases in velocity.

Unlike the treatments that elicited increases in v_{max}, neither of the treatments that caused decreases in v_{max} responded as predicted to the hypothesis with regards to the P_{max} v_{max} relationship. The P_{max} v_{max} relationship was significantly different for the gloves and not significantly different for the dragsuit. The gloves showed a significant increase in the v_{max} adjusted ln(P_{max}). This finding runs contrary to the MPM as a decrease in F_{prop} with no change in F_{res} is expected to cause no change in the P_{max} v_{max} relationship. Should the MPM be valid, this deviation must be explainable. The most likely explanation is that the gloves unintentionally increased F_{res}. Not all forces exerted by a swimmer's hands on the water are opposite to the direction motion (F_{prop}). Typically some of the force is directed downward increasing the height of the swimmer in the water above that of buoyancy alone. Logically, the gloves will also decrease this vertically directed force causing the swimmer to swim lower in water. This change in body position increases the front exposed area of the swimmer under the water and therefore could increase F_{res}.

Contrary to the hypothesis, the dragsuit did not show a significant difference in the P_{max} v_{max} relationship. This finding is also contradictory to the MPM which postulates that an increase in F_{res} with no change in F_{prop} should lead to an increase in the ratio of P_{max} to v_{max}. Interestingly despite showing no significant difference, the dragsuit caused the largest change in the v_{max} adjusted $\ln(P_{max})$ at almost twice that of any other treatment. In comparison to the other treatment conditions, the covariate and the subject factors accounted for a considerably large portion of the total variance. The covariate had an F-ratio of 33.2 and subject had an F-ratio of 30.4 for the dragsuit in comparison to average F-ratios of 5.0 for the covariate and 10.0 for subject of the other three treatments. Perhaps the variance in the independent variable was improperly attributed to the subject and covariate factors instead of the treatment based on the specific results seen. If this is the case, similar testing with a different subject population would show the expected results.

Question: What is the relationship between P_{max} and F_{res} obtained from the Velocity Perturbation Model?

Hypothesis: The relationship between P_{max} and F_{res} obtained from the VPM will be quadratic, but with a low level of agreement due to the large level of random error in the VPM.

Analysis: Correlations coefficients for linear, power, and polynomial fits were calculated between P_{max} and F_{res} of the VPM. The fits were compared against theoretical expectations.

Answer: The relationship between P_{max} and F_{res} was analyzed using a linear fit and found to have a correlation of $R = 0.83$. While this is a significant correlation ($p < 0.05$), given the similarity of the two measures it is a relatively weak relationship. On this count, the hypothesis is correct. The hypothesis also predicts that the relationship is best described as quadratic. This prediction was based on several factors. F_{res} from the VPM is assumed to be proportional to velocity squared. If the variation in F_{res} between individuals is relatively small, then F_{res} can also be expected to be approximately proportional to velocity squared. This assumption holds fairly well when examining the data of Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997). As the first sub-study indicated that the best power fit for P_{max} vs. v_{max} showed a relationship with P_{max} proportional to $v_{max}^{3.8}$, it was logical to expect the relationship between P_{max} and F_{res} to be approximately quadratic. However, the large random error inherent in the VPM calculation of F_{res} made the power and polynomial calculations inappropriate. Both relationships showed minimal deviation from linearity and both were concave down. Based on these two characteristics, the linear fit was chosen as the most informative.

Question: Can the Velocity Perturbation Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The VPM can not distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Analysis: Differences in the coefficient of drag (k) between the standard and equipment treatments were analyzed using planned comparisons for a repeated measures ANOVA. These planned comparisons take the form of paired t-tests (Keppel & Wickens, 2004) $\alpha = 0.05$.

Answer: No differences in k were detected between any of the equipment treatment conditions and the standard condition. No difference is expected for the paddles and the gloves as they are not expected to alter F_{res}. However, a difference is expected for the wetsuit and dragsuit. As no difference was detected, this indicates that the VPM was not able to distinguish between changes in F_{res} and F_{prop}. The random error in the VPM is large and it is possible that a much larger number of subjects may yield better results for the VPM. Nevertheless because changes were detected using the MPM, the VPM shows less sensitivity to changes in F_{res} than the MPM. Similarly it can also be concluded that the VPM can not be used to detect differences between small changes in the swimming condition for a single individual as would be useful for assessing the effectiveness of technical changes.

Question: Can the Max Power Model distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}?

Hypothesis: The MPM can distinguish between changes in F_{res} and F_{prop} that have similar effects on v_{max}.

Analysis: This analysis is based on the statistical procedures used to answer the previous research questions.

Answer: This research question is answered in the next section.

Validity and Usefulness of the Max Power Model

The uniting theme of the present study has been the development and validation of the MPM. The goal of the MPM is to provide an easily accessible method to detect, separate, and quantify differences in F_{prop} and F_{res}. The primary difficulty encountered in this venture has been the lack of a valid gold standard methodology for comparison. In order to overcome this difficulty, two actions were taken. First, the MPM was compared to the most widely accepted and evaluated methodology using assisted and resisted swimming to compute F_{res}, the VPM. Second, the sensitivity of the MPM to independent modifications of F_{prop} and F_{res} was tested.

Evaluation of the MPM using the VPM proved to be unhelpful. In evaluation with independent modifications of F_{prop} and F_{res}, the VPM was found to be either invalid or encumbered with a very large random error. This made comparison of the MPM to the VPM useless in terms of validating the MPM.

The results of the sensitivity of the MPM to independent modifications of F_{prop} and F_{res} was discussed in detail above. The primary problem with using this approach is the difficulty in isolating F_{res} and F_{prop} as they are inherently linked. While the results of the study did not fit directly with those predicted by the MPM, they did show promise. The validity of the MPM can be examined in two more ways. The first is a simple examination of a plot of the average values of P_{max} and v_{max} for each of the five equipment conditions (Figure 1). The MPM predicts that the standard, gloves, and paddles conditions should fall on a single curve with the dragsuit displaced above the curve and the wetsuit displaced below the curve. As seen in Figure 1, this prediction is accurate.

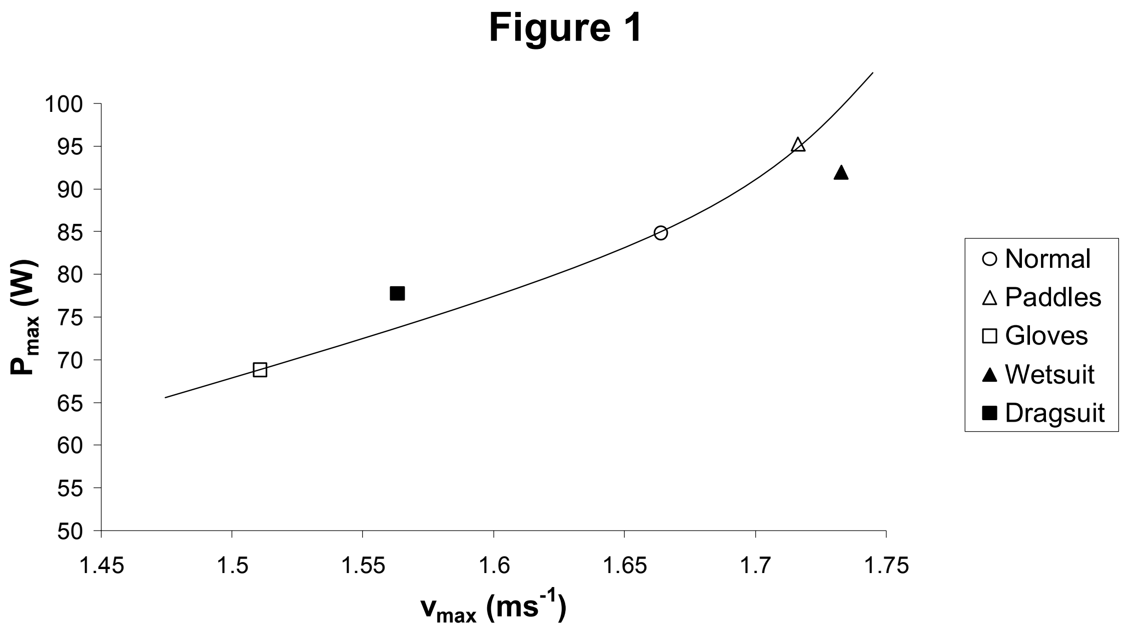

FIGURE 1 - Average values of P_{max} and v_{max} for each of the equipment treatment conditions.

The second examination of the MPM harkens back to the development of face validity in the chapter 2. The face validity of the MPM is based on, but does not rely on, three assumptions involving the change in velocity with the addition of an external load (F_{load}). First, F_{load} vs. velocity is assumed to be linear. Second, changes in F_{res} are expected to change the slope of the F_{load} vs. velocity curve, but not the F_{load} intercept (F_{max}). Third, changes in F_{prop} are expected to change F_{max}, but not the slope of the F_{load} vs. velocity curve. Figure 2 shows a plot of the individual F_{load} vs. velocity points for all ten subjects of the equipment testing procedure. The points were standardized on both axis. The velocity axis was standardized by calculating the velocity of each trial (using all treatment conditions) as a percentage of the subject's standard condition v_{max}. The

F_{load} standardization was a bit more complicated. The F_{max} was predicted for each subject individually for the standard condition using a line of best fit. The F_{load}s of all treatment conditions were standardized as a percentage of the predicted F_{max} for the standard condition. The three assumptions made in the development of the face validity of the MPM can be evaluated using Figure 2. The assumption of linearity holds as each of the linear correlations is greater than R = 0.98. Furthermore, the strong relationship assures that the standardization was successful.

Figure 2

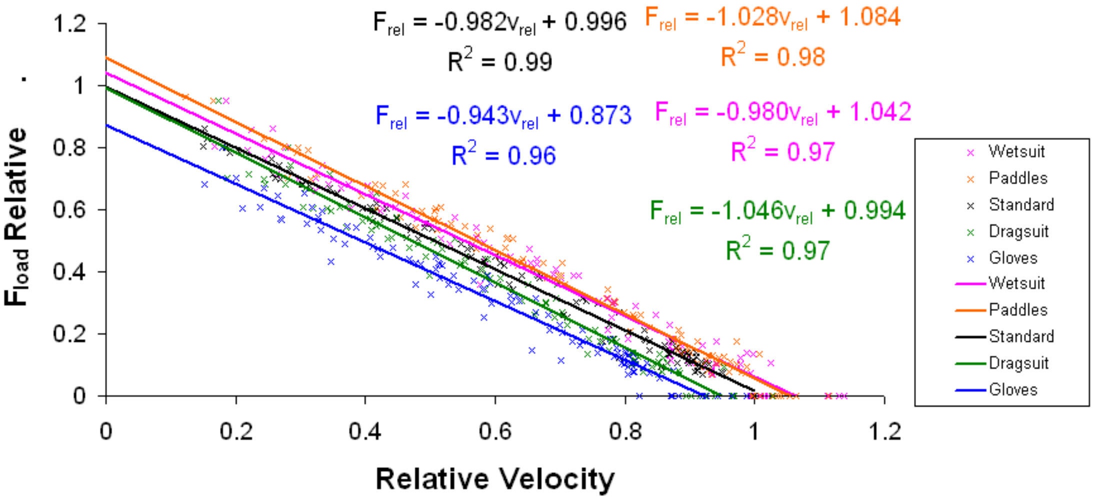

FIGURE 2 - A graph of F_{load} vs. velocity for all subjects. Velocity was standardized using v_{max} from the standard condition for each individual. F_{load} was standardized using the predicted F_{max} for the standard condition of each individual.

The second and third assumptions are more difficult to evaluate. Upon initial examination, the obtained values do not fit with the assumptions. It is expected that the treatment conditions that modify F_{res} (wetsuit and dragsuit) will change the slope of the line with respect to the standard conditions, while the treatment conditions that do not modify F_{res} (paddles and gloves) will not affect the slope. Analysis with a t-test, $\alpha = 0.05$ (Wright, 1978) shows significant differences in slope for the dragsuit, paddles, and gloves, but not the wetsuit (Table 1). This indicates that three of the predictions were incorrect and only one correct (dragsuit). It is expected that the treatment conditions that modify F_{prop} (paddles and gloves) will change the F_{load} intercept (F_{max}) with respect to the standard conditions, while the treatment conditions that do not modify F_{prop} (wetsuit and dragsuit) will not affect F_{max}. Analysis with a t-test, $\alpha = 0.05$ (Wright, 1978) shows significant differences in F_{max} for the wetsuit, paddles, and gloves, but not the dragsuit (Table 1). This show more promise for the assumptions, with three of the four predictions being correct. However, in all the assumptions are correct only 50% of the time.

Table 1

		Standard	Paddles	Gloves	Wetsuit	Dragsuit
Slope	Value	-0.982	-1.028	-0.943	-0.980	-1.046
	Diff from Standard		-0.046*	0.039*	0.002	-0.064*
	% Diff From Standard		4.7	-4.0	-0.2	6.6
Intercept	Value	0.996	1.085	0.873	1.042	0.994
	Diff from Standard		0.089*	-0.123*	0.046*	-0.002
	% Diff From Standard		8.9	-12.4	4.6	-0.2

* Significantly different from the standard condition ($p < 0.05$)

TABLE 1 - Values for the slope and intercept of the standardized F_{load} vs. velocity graph. Absolute and Percentage differences from the standard condition are listed with statistically significantly differences indicated.

The key in understanding this gap is found in a statement in Chapter 2, "More likely [the finding of linearity] implies that our model is simplistic and that the slope and the intercept of the graph can not be considered independent of one another." The most logical link of the slope and intercept would be that an increase in the intercept corresponds with an increase in the absolute value of the slope. With this in mind, the data was corrected using the assumption that the slope of the standard, gloves, and paddles conditions were the same. The correction was accomplished by first making a plot of slope vs. intercept for these three points. A line with a slope of -0.3966 and R = 0.99 was fit to these three points. Based on this regression, the slopes of F_{load} vs. velocity for all of the treatment conditions were corrected for differences in intercept. Statistical detection of differences was accomplished in the same way with measures of variance assumed to remain the same (Table 2).

Table 2

		Standard	Paddles	Gloves	Wetsuit	Dragsuit
Slope	Value	-0.982	-0.993	-0.992	-0.962	-1.047
	Diff from Standard		-0.011	-0.010	0.020	-0.065*
	% Diff From Standard		1.1	1.0	-2.0	6.6
Intercept	Value	0.996	1.085	0.873	1.042	0.994
	Diff from Standard		0.089*	-0.123*	0.046*	-0.002
	% Diff From Standard		8.9	-12.4	4.6	-0.2

* Significantly different from the standard condition ($p < 0.05$)

TABLE 2 - Values for the intercept corrected slope and intercept of the standardized F_{load} vs. velocity graph. Absolute and Percentage differences from the standard condition are listed with statistically significantly differences indicated.

After the correction of the slope for the intercept, the assumptions look much more reasonable. The wetsuit and drag suit now change the slope of the line in the directions expected. This may be in a sense a self-fulfilling prophecy as the manipulation is likely beyond the robustness of the data supporting it. Nevertheless, simple visual analysis of Figure 2 would indicate the assumptions are certainly reasonable, and the slope correction provides a platform for future analysis.

Based upon these results, use of the graph of F_{load} vs. velocity does not appear able to stand alone. This was expected and exemplifies the need for the MPM. However, the graph of F_{load} vs. velocity is not without its uses. One of the current shortcomings of the MPM is the differentiation of F_{prop} when differences in F_{res} also occur. Perhaps the incorporation of F_{max} intercepts from the F_{load} vs. velocity graph into the MPM could fill this void.

The potential uses of the MPM suggest that continued attempts for validation are warranted. The MPM has been shown to require small subject numbers and also has the ability to detect small differences. This could be useful in evaluating F_{res} and F_{prop} for treatments such as swimming suit comparison and anthropometric differences among subjects. Furthermore, it is possible that the MPM may be reliable enough to detect differences in F_{res} and F_{prop} both between individuals and between changes in technique or due to training for a single individual. The MPM is the most effective assisted and resisted method for detecting, separating, and quantifying differences in F_{prop} and F_{res}.

Suggestions for future study

Future study in the area of assisted and resisted swimming should focus on several areas. Future study of the MPM should initially focus on the further validation of the method. This can be accomplished through the testing of different equipment conditions expected to independently modify either F_{prop}, such as fins, or F_{res}, perhaps drag suits with different size pockets. As opposed to the present study which used a repeated measures design, future studies may be better served through use of an independent groups design for two reasons. First, the use of v_{max} as a covariate accounts for a significant portion of the variability between subjects and thus the independent groups design would have sufficient power without extremely large subject numbers. Second, it appears that the differences in individual response to equipment treatment conditions is fairly large. Larger subject numbers would allow for a more accurate portrayal of the general population and might also show responses that are closer to independent modification of F_{prop} and F_{res} as desired. Further validation of the MPM could also be accomplished through comparisons of the MPM with other methodologies for determining F_{res} such as the MAD System. Beyond validation, there are several related areas of study that would be interesting regardless of the validity of the MPM. In particular it would be interesting to see if other forms of underwater kicking would show the same slope of the $\ln(P_{max})$ vs. v_{max} line as underwater dolphin kick. Also of interest is whether pulling would show the same P_{max} v_{max} relationship as swimming. Finally, a more in depth analysis of the F_{load} vs. velocity graph including the interdependence of slope and intercept and use with the MPM would provide for a broad base on knowledge in the area of resisted swimming.

Conclusion

The relationship between P_{max} and v_{max} and the Max Power Model are a significant step forward in the use of tethered swimming as means to gain insight into the propulsive and resistive forces experienced during swimming. This study has progressed the P_{max} v_{max} relationship from assumed linear correlations to a reasonable model to easily detect, separate, and quantify differences in F_{prop} and F_{res}. While the MPM requires further development it shows promise as an important tool for researchers and swimming coaches alike.

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APPENDIX A: RACK CALIBRATIONS

Calibrated force in Newtons for each plate of each rack used to develop the Max Power Model.

	Rack Number									
Plate #	1	2	3	4	5	6	7	8	9	10
1		8.8	8.2	10.1			15.2			12.4
2	10.1	10.8	10.2	12.1	9.8	10.7	17.5			14.5
3	12.1	13.0	12.2	14.2	11.8	13.0	19.9			16.7
4	14.1	15.2	14.2	16.2	13.8	15.3	22.3			18.8
5	16.0	17.3	16.2	18.3	15.8	17.6	24.7		31.4	21.0
6	18.0	19.5	18.2	20.4	17.9	19.9	27.0			23.1
7	20.0	21.6	20.2	22.4	19.9	22.2	29.4	23.6	37.0	25.3
8	21.9	23.7	22.2	24.5	21.9	24.5	31.8	25.9	41.6	27.4
9	23.9	25.9	24.2	26.5	23.9	26.8	34.2			29.6
10	25.9	28.0	26.2	28.6	25.9	29.1	36.5	27.9	45.4	31.7
11	27.8	30.1	28.2	30.6	27.9	31.4	38.9			33.9
12	29.8	32.3	30.2	32.7	29.9	33.7	41.3	33.7	49.5	36.0
13	31.8	34.4	32.2	34.8	31.9	36.0	43.7			38.2
14	33.7	36.5	34.2	36.8	33.9	38.3	46.0		54.6	40.3
15	35.7	38.7	36.2	38.9	35.9	40.6	48.4			42.4
16	37.7	40.8	38.2	40.9	37.9	42.9	50.8	45.8	58.0	44.6
17	39.6	42.9	40.2	43.0	39.9	45.2	53.2			46.7
18	41.6	45.1	42.2	45.0	41.9	47.5	55.5	53.5	65.5	48.9
19	43.6	47.2	44.2	47.1	43.9	49.7	57.9			51.0
20	45.5	49.3	46.2	49.2	45.9	52.0	60.3	55.4	69.6	53.2
21	47.5	51.5	48.2	51.2	47.9	54.3	62.6			55.3
22	49.5	53.6	50.2	53.3	49.9	56.6	65.0			57.5
23	51.4	55.7	52.2	55.3	51.9	58.9	67.4			59.6
24	53.4	57.9	54.2	57.4	53.9	61.2	69.8			61.8
25	55.4	60.0	56.2	59.5	55.9	63.5	72.1			63.9
26	57.3	62.2	58.2	61.5	57.9	65.8	74.5			66.1
27	59.3	64.3	60.2	63.6	59.9	68.1	76.9			68.2
28	61.3	66.4	62.2	65.6	61.9	70.4	79.3			70.4
29	63.2	68.6	64.2	67.7	63.9	72.7	81.6			72.5
30	65.2	70.7	66.2	69.7	65.9	75.0	84.0			74.6
31	67.2	72.8	68.2	71.8	67.9	77.3	86.4			76.8
32	69.1	75.0	70.2	73.9	69.9	79.6	88.8			78.9
33	71.1	77.1	72.2	75.9	71.9	81.9	91.1			81.1
34	73.1	79.2	74.2	78.0	73.9	84.2	93.5			83.2
35	75.0	81.4	76.2	80.0	75.9	86.5	95.9			85.4
36	77.0	83.5	78.2	82.1	77.9	88.8	98.3			87.5
37	79.0	85.6	80.2	84.1	79.9	91.1	100.6			89.7
38	80.9	87.8	82.2	86.2	81.9	93.4	103.0			91.8
39	82.9	89.9	84.2	88.3	84.0		105.4			94.0
40	84.9				86.0					

Calibrated force in Newtons for each plate of each rack used to develop the Max Power Model.

	Rack Number									
Plate #	11	21	22	31	32	41	51	52	61	100
1	7.9	7.6	5.2	12.5	12.0	6.9	7.5	9.9	9.6	9.4
2	10.0	9.6	7.1	14.5	14.0	9.2	9.5	11.9	11.7	11.3
3	12.0	11.6	9.1	16.6	16.0	11.5	11.5	13.9	13.7	13.2
4	14.1	13.5	11.0	18.6	18.0	13.8	13.5	15.9	15.8	15.1
5	16.2	15.5	12.9	20.6	20.0	16.1	15.5	17.9	17.8	17.0
6	18.3	17.5	14.8	22.7	22.0	18.4	17.4	19.9	19.8	18.9
7	20.4	19.4	16.7	24.7	24.0	20.7	19.4	21.9	21.9	20.9
8	22.5	21.4	18.7	26.7	26.0	23.1	21.4	23.9	23.9	22.8
9	24.6	23.4	20.6	28.8	28.0	25.4	13.4	25.9	26.0	24.7
10	26.7	25.3	22.5	30.8	30.0	27.7	25.4	27.9	28.0	26.6
11	28.8	27.3	24.4	32.9	32.0	30.0	27.4	29.9	30.0	28.5
12	30.8	29.3	26.3	34.9	34.0	32.3	29.4	31.9	32.1	30.4
13	32.9	31.2	28.2	36.9	36.0	34.6	31.4	33.9	34.1	32.4
14	35.0	33.2	30.2	39.0	38.0	36.9	33.3	35.9	36.2	34.3
15	37.1	35.2	32.1	41.0	40.0	39.3	35.3	37.9	38.2	36.2
16	39.2	37.1	34.0	43.0	41.9	41.6	37.3	39.9	40.2	38.1
17	41.3	39.1	35.9	45.1	43.9	43.9	39.3	41.9	42.3	40.0
18	43.4	41.1	37.8	47.1	45.9	46.2	41.3	43.9	44.3	41.9
19	45.5	43.1	39.7	49.2	47.9	48.5	43.3	45.9	46.4	43.9
20	47.5	45.0	41.7	51.2	49.9	50.8	45.3	47.9	48.4	45.8
21	49.6	47.0	43.6	53.2	51.9	53.1	47.2	49.9	50.4	47.7
22	51.7	49.0	45.5	55.3	53.9	55.5	49.2	51.9	52.5	49.6
23	53.8	50.9	47.4	57.3	55.9	57.8	51.2	53.9	54.5	51.5
24	55.9	52.9	49.3	59.3	57.9	60.1	53.2	55.9	56.5	53.4
25	58.0	54.9	51.3	61.4	59.9	62.4	55.2	57.9	58.6	55.4
26	60.1	56.8	53.2	63.4	61.9	64.7	57.2	59.9	60.6	57.3
27	62.2	58.8	55.1	65.5	63.9	67.0	59.2	61.9	62.7	59.2
28	64.2	60.8	57.0	67.5	65.9	69.3	61.1	63.9	64.7	61.1
29	66.3	62.7	58.9	69.5	67.9	71.7	63.1	65.9	66.7	63.0
30	68.4	64.7	60.8	71.6	69.9	74.0	65.1	67.9	68.8	65.0
31	70.5	66.7	62.8	73.6	71.9	76.3	67.1	69.9	70.8	66.9
32	72.6	68.6	64.7	75.6	73.9	78.6	69.1	71.9	72.9	68.8
33	74.7	70.6	66.6	77.7	75.9	80.9	71.1	73.9	74.9	70.7
34	76.8	72.6	68.5	79.7	77.8	83.2	73.1	75.9	76.9	72.6
35	78.9	74.5	70.4	81.7	79.8	85.5	75.0	78.0	79.0	74.5
36	80.9	76.5	72.3	83.8	81.8	87.9	77.0	80.0	81.0	76.5
37	83.0	78.5	74.3	85.8	83.8	90.2	79.0	82.0	83.1	78.4
38	85.1	80.4	76.2	87.9	85.8	92.5	81.0	84.0	85.1	80.3
39	87.2	82.4	78.1	89.9	87.8	94.8	83.0	86.0	87.1	82.2
40	89.3	84.4		91.9	89.8	97.1	85.0	88.0	89.2	84.1

Calibrated force in Newtons for each plate of each rack used to develop the Max Power Model.

	Rack Number								
Plate #	110	120	301	302	302+	302++	303	303+	303++
1	5.7	3.8	6.1	12.4	34.6	56.9	5.9	26.6	47.2
2	7.8	6.1	8.5	14.5	36.7	59.0	7.9	28.6	49.2
3	9.8	8.4	10.9	16.6	38.7	61.0	10.0	30.6	51.3
4	11.9	10.7	13.3	18.7	40.8	63.0	12.0	32.6	53.4
5	13.9	13.0	15.7	20.8	42.9	65.0	14.0	34.7	55.5
6	15.9	15.3	18.1	22.9	45.0	67.0	16.1	36.7	57.5
7	18.0	17.6	20.5	25.0	47.0	69.0	18.1	38.7	59.6
8	20.0	19.9	22.9	27.1	49.1	71.0	20.1	40.8	61.7
9	22.1	22.2	25.3	29.2	51.2	73.0	22.2	42.8	63.7
10	24.1	24.5	27.7	31.3	53.2	75.0	24.2	44.8	65.8
11	26.2	26.8	30.1	33.4	55.3	77.0	26.2	46.8	67.9
12	28.2	29.1	32.5	35.5	57.4	79.0	28.3	48.9	70.0
13	30.2	31.4	34.9	37.6	59.4	81.0	30.3	50.9	72.0
14	32.3	33.7	37.3	39.7	61.5	83.0	32.4	52.9	74.1
15	34.3	36.0	39.7	41.8	63.6	85.0	34.4	54.9	76.2
16	36.4	38.3	42.1	43.9	65.6	87.0	36.4	57.0	78.3
17	38.4	40.6	44.5	46.0	67.7	89.0	38.5	59.0	80.3
18	40.5	42.9	46.9	48.1	69.8	91.0	40.5	61.0	82.4
19	42.5	45.2	49.3	50.2	71.9	93.0	42.5	63.1	84.5
20	44.6	47.5	51.7	52.3	73.9	95.0	44.6	65.1	86.5
21	46.6	49.8	54.1	54.4	76.0	97.0	46.6	67.1	88.6
22	48.6	52.0	56.5	56.5	78.1	99.0	48.6	69.1	90.7
23	50.7	54.3	58.9	58.6	80.1	101.0	50.7	71.2	92.8
24	52.7	56.6	61.3	60.7	82.2	103.0	52.7	73.2	94.8
25	54.8	58.9	63.7	62.8	84.3	105.0	54.8	75.2	96.9
26	56.8	61.2	66.1	64.8	86.3	107.0	56.8	77.3	99.0
27	58.9	63.5	68.5	66.9	88.4	109.0	58.8	79.3	101.0
28	60.9	65.8	70.9	69.0	90.5	111.0	60.9	81.3	103.1
29	63.0	68.1	73.3	71.1	92.5	113.0	62.9	83.3	105.2
30	65.0	70.4	75.7	73.2	94.6	115.0	64.9	85.4	107.3
31	67.0	72.7		75.3	96.7	117.0	67.0	87.4	109.3
32	69.1	75.0							
33	71.1	77.3							
34	73.2	79.6							
35	75.2	81.9							
36	77.3	84.2							
37	79.3	86.5							
38	81.3	88.8							
39	83.4	91.1							
40	85.4	93.4							

Calibrated force in Newtons for each plate of the extended height rack used to assess the validity of the Max Power Model.

Plates	Standard	With Saddlebags
1	16.2	119.2
2	21.3	124.5
3	26.4	129.7
4	31.5	135.0
5	36.7	140.3
6	41.8	145.5
7	46.9	150.8
8	52.0	156.0
9	57.1	161.3
10	62.2	166.5
11	67.3	171.8
12	72.4	177.1
13	77.5	182.3
14	82.6	187.6
15	87.8	192.8
16	92.9	198.1
17	98.0	203.3
18	103.1	208.6
19	108.2	213.9
20	113.3	219.1
21	118.4	224.4
22	123.5	229.6
23	128.6	234.9
24	133.7	240.1
25	138.8	245.4
26	144.0	250.7
27	149.1	255.9
28	154.2	261.2
29	159.3	266.4
30	164.4	271.7

APPENDIX B: INDIVIDUAL DATA

Development of the Max Power Model

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Back	Female	55.1	171.3	15	1.331	23.54
Back	Female	38.4	152.0	11	1.284	24.74
Back	Female	49.0	154.1	12	1.229	32.05
Back	Female	72.4	174.0	18	1.258	31.88
Back	Male	75.5	180.6	19	1.662	79.51
Back	Male	87.1	191.3	21	1.704	83.39
Back	Male	85.1	191.6	21	1.722	88.08
Back	Male	80.8	186.7	19	1.655	105.55
Back	Male	62.2	136.8	13	1.405	38.64
Back	Male	44.0	148.0	13	1.345	25.37
Back	Male	75.1	187.9	17	1.497	52.54
Back	Male	92.4	191.0	20	1.435	63.03
Breast	Female	48.3	171.0	14	1.029	22.17
Breast	Female	68.9	169.3	19	1.268	44.26
Breast	Female	61.9	168.2	16	1.202	33.18
Breast	Female	43.2	160.6	10	0.730	9.69
Breast	Male	84.2	170.0	19	1.058	39.38
Breast	Male	36.4	183.6	16	1.183	59.07
Breast	Male	35.4	143.1	9	0.844	14.04
Breast	Male	64.7	178.8	15	1.114	48.85
Breast	Male	53.4	160.8		1.040	24.84
Dolphin	Male	80.7	178.0	21	1.161	26.77
Dolphin	Male	87.9	183.0	22	1.567	60.46
Dolphin	Male	78.8	179.4	21	1.562	43.78
Dolphin	Male	81.9	190.0	20	1.446	41.65
Dolphin	Male	74.4	174.3	20	1.306	44.33
Dolphin	Male	74.7	179.6	19	1.885	48.88
Dolphin	Female	61.3	166.3	19	1.623	43.03
Dolphin	Female	66.0	158.1	27	1.201	17.05
Dolphin	Male	77.4	178.7	24	1.341	33.22
Dolphin	Female	65.5	165.2	25	1.527	30.20
Dolphin	Male	68.6	175.6	21	1.380	31.35
Dolphin	Male	79.4	181.2	25	1.358	33.76
Dolphin	Female	66.4	174.1	21	1.454	28.24
Dolphin	Male	89.1	182.2	21	1.674	78.39
Fly	Female	81.1	172.3	18	1.405	46.80
Fly	Female	69.4	169.9	15	1.284	33.99
Fly	Male	83.4	177.5	20	1.418	65.79
Fly	Male	73.4	176.6	15	1.619	65.81
Fly	Male	52.5	168.6	13	1.214	23.40
Fly	Male	75.0	179.3	17	1.458	53.87
Fly	Male	67.6	175.4	21	1.780	97.43
Fly	Male	93.3	186.1	19	1.807	89.95
Fly	Male	49.9	155.0	11	1.250	26.80

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Female	74.9	165.5	14	1.255	21.82
Front Crawl	Female	49.2	157.0		1.279	19.88
Front Crawl	Female	51.5	171.4	14	1.395	29.11
Front Crawl	Female	83.8	171.0	16	1.111	19.42
Front Crawl	Female	59.4	159.0	16	1.561	51.03
Front Crawl	Female	54.9	170.7	15	1.283	30.48
Front Crawl	Female	63.9	173.9	16	1.493	43.06
Front Crawl	Female	82.0	180.7	15	1.182	20.18
Front Crawl	Female	67.5	174.4	16	0.986	11.57
Front Crawl	Female	50.0	163.0	16	1.416	34.18
Front Crawl	Female	58.3	173.6	16	1.424	30.02
Front Crawl	Female	49.7	164.1	17	1.470	44.66
Front Crawl	Female	73.7	171.1	16	1.480	46.36
Front Crawl	Female	56.1	164.4	14	1.448	37.04
Front Crawl	Female	63.6	180.2	15	1.352	35.03
Front Crawl	Female	62.7	169.0	14	0.991	13.85
Front Crawl	Female	54.5	166.0	14	1.102	16.49
Front Crawl	Female	75.9	172.1	16	1.260	23.12
Front Crawl	Female	51.2	160.7	13	1.515	45.61
Front Crawl	Female	41.4	156.8	13	1.601	34.31
Front Crawl	Female	70.4	167.0	15	1.633	65.48
Front Crawl	Female	55.7	173.4	17	1.442	32.77
Front Crawl	Female	54.2	154.3	16	1.589	34.29
Front Crawl	Female	63.2	161.9	15	1.488	39.12
Front Crawl	Female	51.7	162.6	16	1.658	68.84
Front Crawl	Female	58.5	172.7	19	1.741	74.30
Front Crawl	Female	51.2	170.2	14	1.514	38.69
Front Crawl	Female	70.2	175.9	16	1.678	58.80
Front Crawl	Female	56.0	160.7	15	1.547	40.35
Front Crawl	Female	62.9	165.7	15	1.611	52.33
Front Crawl	Female	51.7	170.2	14	1.545	38.98
Front Crawl	Female	54.0	160.0	16	1.532	36.27
Front Crawl	Female	57.0	165.7	15	1.725	51.61
Front Crawl	Female	82.9	177.8	16	1.580	62.27
Front Crawl	Female	63.7	167.0	17	1.665	65.74
Front Crawl	Female	70.7	170.2	15	1.627	45.20
Front Crawl	Female	62.7	172.1	16	1.687	46.15
Front Crawl	Female	71.9	173.0	21	1.628	61.62
Front Crawl	Female	57.0	175.5	21	1.574	48.51
Front Crawl	Female	69.7	165.1	18	1.595	59.26
Front Crawl	Female	53.2	160.0	18	1.541	57.14
Front Crawl	Female	62.6	166.3	18	1.613	49.00
Front Crawl	Female	52.5	167.7	18	1.579	45.58
Front Crawl	Female	74.0	174.2	18	1.551	42.83

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Female	63.6	167.4	18	1.610	61.38
Front Crawl	Female	62.9	168.9	19	1.634	60.39
Front Crawl	Female	76.1	176.4	22	1.681	86.05
Front Crawl	Female	66.6	167.8	18	1.552	51.62
Front Crawl	Female	60.8	170.0	19	1.506	42.23
Front Crawl	Female	77.6	177.5	19	1.585	55.87
Front Crawl	Female	64.4	168.0	21	1.545	65.65
Front Crawl	Female	65.6	174.5	21	1.588	57.86
Front Crawl	Female	56.2	162.0	21	1.521	42.45
Front Crawl	Female	61.4	170.0	19	1.573	51.74
Front Crawl	Female	56.4	169.0	21	1.505	42.99
Front Crawl	Female	63.3	169.4	14	1.436	42.42
Front Crawl	Female	64.2	172.3	15	1.418	47.73
Front Crawl	Female	59.5	164.4	17	1.575	57.35
Front Crawl	Female	59.5	165.2	15	1.375	43.80
Front Crawl	Female	46.8	164.7	14	1.426	31.25
Front Crawl	Female	56.2	163.6	16	1.376	32.53
Front Crawl	Female	63.2	168.6	15	1.392	38.70
Front Crawl	Female	38.4	152.0	11	1.485	28.04
Front Crawl	Female	86.3	176.5	16	1.465	51.52
Front Crawl	Female	69.4	169.9	15	1.423	36.28
Front Crawl	Female	49.3	155.0	14	1.510	24.62
Front Crawl	Female	32.2	131.0	8	0.780	5.43
Front Crawl	Female	48.3	171.0	14	1.225	15.89
Front Crawl	Female	72.3	168.0	16	1.282	19.79
Front Crawl	Female	43.6	151.7	13	1.464	27.86
Front Crawl	Female	56.7	158.8	13	1.398	23.82
Front Crawl	Female	57.6	163.1	13	1.518	31.40
Front Crawl	Female	42.6	147.7	10	1.148	10.52
Front Crawl	Female	61.9	168.2	16	1.582	49.10
Front Crawl	Female	63.3	174.2	16	1.510	45.77
Front Crawl	Female	64.5	157.0	13	1.161	25.58
Front Crawl	Female	43.2	160.6	10	1.008	10.70
Front Crawl	Female	67.2	171.3	15	1.547	50.98
Front Crawl	Female	46.5	152.6	11	1.325	22.21
Front Crawl	Female	41.5	156.2	13	1.241	21.40
Front Crawl	Female	32.5	137.3	11	1.451	27.21
Front Crawl	Female	44.5	158.4	14	1.450	26.11
Front Crawl	Female	46.8	154.0	11	1.460	27.55
Front Crawl	Female	61.1	155.1	13	1.432	40.95
Front Crawl	Female	41.2	144.8	11	1.160	19.16
Front Crawl	Female	54.4	167.7	12	1.525	43.94
Front Crawl	Female	44.3	158.7	12	1.487	26.67
Front Crawl	Female	65.9	169.8	12	1.268	31.20

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Female	57.8	153.5	14	1.242	24.69
Front Crawl	Female	50.5	155.5	11	1.353	22.33
Front Crawl	Female	55.8	154.9	13	1.525	43.42
Front Crawl	Female	27.5	126.4	7	1.208	13.07
Front Crawl	Female	48.5	153.2	13	1.397	30.69
Front Crawl	Female	37.4	136.3	9	1.015	11.83
Front Crawl	Female	41.4	154.1	10	1.386	20.32
Front Crawl	Female	56.1	160.2	16	1.365	15.79
Front Crawl	Female	29.3	136.2	10	1.174	9.99
Front Crawl	Female	42.9	150.0	11	1.265	16.25
Front Crawl	Female	48.9	152.7	13	1.411	30.55
Front Crawl	Female	64.7	177.8	14	1.373	31.47
Front Crawl	Female	51.9	159.0	12	1.334	29.65
Front Crawl	Female	64.4	164.5	13	1.636	55.05
Front Crawl	Female	24.9	125.6	8	0.944	5.67
Front Crawl	Female	32.4	137.2	9	1.347	16.98
Front Crawl	Female	90.1	157.8	14	1.342	34.57
Front Crawl	Female	43.8	148.3	12	1.303	24.14
Front Crawl	Female	34.3	144.7	11	1.453	23.72
Front Crawl	Female	50.2	153.9	10	1.288	23.71
Front Crawl	Female	36.1	138.1	10	1.331	17.96
Front Crawl	Female	58.7	159.4	13	1.321	30.98
Front Crawl	Female	55.0	166.4	15	1.502	33.65
Front Crawl	Female	38.7	147.1	12	1.205	12.09
Front Crawl	Female	48.5	156.3	11	1.385	24.82
Front Crawl	Female	51.3	162.7	11	1.529	44.48
Front Crawl	Female	62.0	169.6	16	1.598	53.39
Front Crawl	Female	69.0	171.3	15	1.616	55.63
Front Crawl	Female	61.7	170.0	16	1.533	37.22
Front Crawl	Female	68.5	170.5	16	1.647	57.51
Front Crawl	Female	62.7	170.2	16	1.545	46.25
Front Crawl	Female	67.1	167.5	14	1.624	46.52
Front Crawl	Female	61.0	174.3	16	1.498	37.57
Front Crawl	Female	55.1	173.6	16	1.476	32.00
Front Crawl	Female	69.3	167.7	14	1.392	28.61
Front Crawl	Female	45.0	156.7	12	1.434	27.89
Front Crawl	Female	71.5	171.0	17	1.588	46.40
Front Crawl	Female	51.3	159.5	12	1.461	33.53
Front Crawl	Female	48.1	156.0	12	1.539	41.73
Front Crawl	Female	41.5	154.4	12	1.436	24.94
Front Crawl	Female	46.5	161.5	11	1.407	21.69

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Female	55.6	155.5	13	1.444	27.76
Front Crawl	Female	45.2	157.5	12	1.429	25.08
Front Crawl	Female	49.6	158.5	14	1.365	32.82
Front Crawl	Female	43.3	155.6	12	1.415	25.61
Front Crawl	Female	37.5	148.5	13	1.428	28.06
Front Crawl	Female	62.0	166.8	13	1.438	43.01
Front Crawl	Female	40.7	150.0	12	1.311	16.67
Front Crawl	Female	51.3	159.6	13	1.386	27.25
Front Crawl	Female	42.7	152.4	12	1.439	40.57
Front Crawl	Female	40.0	149.7	12	1.318	21.49
Front Crawl	Female	31.5	138.6	10	1.389	19.80
Front Crawl	Female	31.7	144.3	10	1.391	20.43
Front Crawl	Female	55.2	157.7	11	1.349	22.47
Front Crawl	Female	32.3	144.0	10	1.302	17.29
Front Crawl	Female	41.5	150.7	12	1.247	14.41
Front Crawl	Female	39.3	143.2	11	1.218	19.15
Front Crawl	Female	31.9	138.0	11	1.230	12.06
Front Crawl	Female	27.7	133.0	10	1.181	10.24
Front Crawl	Female	48.2	146.0	10	1.300	21.48
Front Crawl	Female	48.5	162.0	14	1.325	23.37
Front Crawl	Female	41.5	148.0	10	1.163	14.11
Front Crawl	Female	29.9	137.5	10	1.155	12.47
Front Crawl	Female	61.3	176.0	14	1.464	35.12
Front Crawl	Female	54.5	161.0	11	1.373	35.57
Front Crawl	Female	34.8	141.2	11	1.284	20.26
Front Crawl	Female	47.2	153.5	12	1.340	25.28
Front Crawl	Female	50.0	162.2	13	1.494	31.26
Front Crawl	Female	61.6	164.0	13	1.418	35.55
Front Crawl	Female	43.8	151.4	14	1.098	13.98
Front Crawl	Female	70.9	162.1	17	1.464	43.05
Front Crawl	Female	31.8	140.0	10	0.930	10.87
Front Crawl	Female	47.5	154.7	12	1.509	32.49
Front Crawl	Female	39.1	154.8	12	1.509	23.45
Front Crawl	Female	31.1	139.1	11	1.464	24.39
Front Crawl	Female	94.9	160.2	14	1.186	32.20
Front Crawl	Female	62.2	158.5	13	1.268	29.82
Front Crawl	Female	62.7	168.0	12	1.421	43.38
Front Crawl	Female	33.3	140.4	8	0.872	10.37
Front Crawl	Female	56.5	160.6	13	1.319	21.80
Front Crawl	Female	57.5	158.0	14	1.486	37.64
Front Crawl	Female	57.7	163.0	13	1.449	40.70
Front Crawl	Female	58.3	164.0	15	1.457	25.70
Front Crawl	Female	60.3	167.4	14	1.522	41.39
Front Crawl	Female	57.7	167.9	14	1.508	35.49

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Female	54.0	171.0	14	1.357	28.52
Front Crawl	Female	59.0	158.5	15	1.456	34.19
Front Crawl	Female	76.8	163.7	15	1.467	47.08
Front Crawl	Female	46.2	156.5	12	1.516	33.56
Front Crawl	Female	50.6	161.1	12	1.417	29.63
Front Crawl	Male			15	1.349	26.35
Front Crawl	Male	56.6	163.5	16	1.275	15.77
Front Crawl	Male			16	1.455	37.64
Front Crawl	Male	76.7	173.5	17	1.741	94.82
Front Crawl	Male				1.606	63.42
Front Crawl	Male	75.1	178.1	16	1.709	54.97
Front Crawl	Male	47.5	159.5	15	1.181	25.37
Front Crawl	Male	55.5	166.1	17	1.534	40.60
Front Crawl	Male			17	1.751	91.00
Front Crawl	Male	65.5	177.8	18	1.754	89.08
Front Crawl	Male	54.7	182.8	16	1.674	61.56
Front Crawl	Male	70.0	182.8	14	1.681	76.36
Front Crawl	Male	58.7	168.9	13	1.601	57.69
Front Crawl	Male	74.1	182.8	17	1.777	86.94
Front Crawl	Male	74.5	177.8	17	1.785	95.49
Front Crawl	Male	65.9	178.4	17	1.732	77.38
Front Crawl	Male	70.6	188.6	16	1.868	93.85
Front Crawl	Male	65.7	174.6	15	1.808	77.97
Front Crawl	Male	82.3	186.1	18	1.834	109.83
Front Crawl	Male	70.5	179.1	16	1.650	73.25
Front Crawl	Male	61.3	175.0	18	1.757	65.75
Front Crawl	Male	71.0	183.0	20	1.836	82.47
Front Crawl	Male	72.6	182.0	18	1.846	94.16
Front Crawl	Male	72.2	186.0	20	1.785	93.38
Front Crawl	Male	74.8	173.6	21	1.691	82.73
Front Crawl	Male	84.4	189.0	18	1.815	103.74
Front Crawl	Male	70.3	179.0	19	1.768	61.13
Front Crawl	Male	69.6	177.0	19	1.831	98.30
Front Crawl	Male	67.7	181.0	19	1.705	76.40
Front Crawl	Male	80.5	187.0	18	1.764	95.21
Front Crawl	Male	76.2	187.0	18	1.740	82.91
Front Crawl	Male	73.2	184.0	20	1.737	73.64
Front Crawl	Male	77.6	183.0	19	1.805	89.23
Front Crawl	Male	85.0	188.0	21	1.818	100.62
Front Crawl	Male	76.8	188.3	18	1.681	70.70
Front Crawl	Male	87.5	177.1	19	1.766	96.88
Front Crawl	Male	72.2	180.0	19	1.796	95.29
Front Crawl	Male	70.2	174.0	22	1.662	70.05
Front Crawl	Male	78.9	191.5	20	1.735	82.80

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Male	79.4	183.0	18	1.768	76.84
Front Crawl	Male	80.6	184.6	21	1.796	93.13
Front Crawl	Male	96.0	182.8	20	1.734	96.02
Front Crawl	Male	75.0	174.8	17	1.508	71.22
Front Crawl	Male	66.5	172.6	17	1.574	56.17
Front Crawl	Male	54.3	166.7	16	1.558	48.55
Front Crawl	Male	47.1	160.5	13	1.428	44.71
Front Crawl	Male	75.1	187.9	17	1.633	80.07
Front Crawl	Male	44.0	148.0	13	1.435	30.49
Front Crawl	Male	36.4	183.6	16	1.684	66.27
Front Crawl	Male	33.4	176.6	15	1.694	74.38
Front Crawl	Male	48.6	157.8	14	1.475	39.13
Front Crawl	Male	63.3	167.7	15	1.498	40.52
Front Crawl	Male	52.5	168.6	13	1.369	29.38
Front Crawl	Male	75.0	179.3	17	1.715	71.12
Front Crawl	Male	68.9	173.0	13	1.458	44.44
Front Crawl	Male	43.7	157.4	13	1.560	33.86
Front Crawl	Male	62.2	177.0	13	1.601	52.96
Front Crawl	Male	53.4	160.8		1.453	41.01
Front Crawl	Male	45.5	148.3	13	1.395	25.16
Front Crawl	Male	54.6	163.8	16	1.439	40.84
Front Crawl	Male	59.9	173.5	13	1.580	40.83
Front Crawl	Male	46.1	158.5	14	1.506	47.05
Front Crawl	Male	70.5	176.3	15	1.565	50.22
Front Crawl	Male	39.4	150.8	12	1.443	36.85
Front Crawl	Male	58.5	168.3	12	1.527	57.40
Front Crawl	Male	65.6	180.7	15	1.624	70.23
Front Crawl	Male	68.1	182.8	13	1.643	71.19
Front Crawl	Male	37.3	143.5	11	1.465	32.27
Front Crawl	Male	68.0	171.1	13	1.566	69.00
Front Crawl	Male	94.5	177.7	14	1.534	71.81
Front Crawl	Male	78.3	172.4	14	1.561	59.53
Front Crawl	Male	60.9	159.2	16	1.613	57.65
Front Crawl	Male	64.4	181.6	14	1.514	57.72
Front Crawl	Male	59.2	169.6	16	1.683	67.29
Front Crawl	Male	62.0	167.2	13	1.687	59.01
Front Crawl	Male	70.1	175.0	14	1.642	67.24
Front Crawl	Male	67.0	176.7	14	1.533	43.74
Front Crawl	Male	71.1	176.8	15	1.550	43.51
Front Crawl	Male	74.5	168.6	13	1.461	45.34
Front Crawl	Male	46.7	150.0	11	1.487	35.22
Front Crawl	Male	77.8	162.0	13	1.169	23.19
Front Crawl	Male	43.2	157.7	12	1.296	24.46
Front Crawl	Male	43.0	141.0	10	1.232	18.03

Stroke	Sex	Mass (kg)	Height(cm)	Age (yrs)	v_{max} (m/s)	P_{max} (W)
Front Crawl	Male	29.3	132.0	10	1.174	10.47
Front Crawl	Male	47.2	152.1	12	1.239	17.86
Front Crawl	Male	71.4	171.5	16	1.725	67.07
Front Crawl	Male	55.6	175.9	16	1.644	54.68
Front Crawl	Male	43.5	148.9	12	1.497	29.10
Front Crawl	Male	28.2	135.4	9	1.222	11.76
Front Crawl	Male	83.5	174.6	16	1.595	61.64
Front Crawl	Male	59.5	173.3	16	1.374	34.88
Front Crawl	Male	74.8	173.5	16	1.425	45.99
Front Crawl	Male	69.7	178.3	16	1.633	65.97
Front Crawl	Male	66.4	173.4	15	1.511	50.44
Front Crawl	Male	65.4	178.1	17	1.504	48.72
Front Crawl	Male	63.5	179.9	16	1.306	35.33
Front Crawl	Male	60.7	180.5	17	1.565	40.24
Front Crawl	Male	39.1	139.5	11	1.322	23.13
Front Crawl	Male	41.4	154.5	12	1.454	26.36
Front Crawl	Male	68.7	177.5	16	1.507	49.34
Front Crawl	Male	99.9	180.0	15	1.603	72.41
Front Crawl	Male	82.6	178.7	17	1.523	53.56
Front Crawl	Male	67.5	175.0	17	1.694	75.03
Front Crawl	Male	64.9	179.3	17	1.668	68.28
Front Crawl	Male	38.6	144.4	11	1.375	22.55

Assessing the Validity of the Max Power Model

Max Power Model Data

	Description		
Subject	Mass (kg)	Height (cm)	Age (Yrs)
1	69.0	168.1	21
2	73.3	178.3	26
3	72.0	176.9	20
4	93.1	197.5	21
5	62.9	181.1	28
6	82.0	182.8	26
7	73.9	178.4	27
8	114.0	188.1	22
9	69.7	186.7	26
10	67.4	173.0	27

	v_{max} (m/s)				
Subject	Normal	Paddles	Wetsuit	Dragsuit	Gloves
1	1.663	1.654	1.697	1.487	1.452
2	1.791	1.887	1.819	1.617	1.657
3	1.823	1.888	1.862	1.683	1.587
4	1.894	1.970	1.943	1.777	1.786
5	1.309	1.459	1.478	1.235	1.294
6	1.430	1.425	1.627	1.383	1.316
7	1.748	1.797	1.765	1.692	1.687
8	1.407	1.497	1.565	1.446	1.294
9	1.641	1.639	1.653	1.547	1.449
10	1.932	1.948	1.921	1.767	1.588

	P_{max} (W)				
Subject	Normal	Paddles	Wetsuit	Dragsuit	Gloves
1	71.51	73.05	83.23	59.37	60.86
2	99.92	113.96	99.45	85.92	81.14
3	98.18	114.41	109.07	87.29	82.82
4	148.23	161.82	155.45	125.67	120.27
5	39.31	50.46	46.54	35.77	34.89
6	57.75	59.04	67.55	56.31	45.17
7	90.15	103.05	101.97	90.24	74.88
8	59.75	77.54	65.16	66.60	55.47
9	63.87	75.38	64.97	60.05	40.64
10	119.81	123.52	125.79	110.18	91.72

Velocity Perturbation Model Data

	Standard		Paddles		Wetsuit		Dragsuit		Gloves	
Subject	F_{res} (N)	k	F_{res} (N)	k	F_{res} (N)	k	F_{res} (N)	k	F_{res} (N)	k
1	69.81	25.25	97.17	35.54	88.01	30.55	57.28	25.89	62.73	29.76
2	57.94	18.06	69.28	19.47	63.70	19.25	66.36	25.39	71.16	25.92
3	96.79	29.11	102.09	28.64	63.05	18.19	78.29	27.65	87.15	34.59
4	124.78	34.79	140.97	36.32	169.26	44.84	114.36	36.23	63.40	19.88
5	40.80	23.81	56.30	26.45	46.30	21.19	36.22	23.76	30.03	17.93
6	78.75	38.51	68.96	33.96	54.61	20.64	51.13	26.73	39.55	22.85
7	61.62	20.17	54.97	17.03	86.75	27.86	66.72	23.30	57.11	20.07
8	37.20	18.78	63.74	28.46	58.82	24.01	74.25	35.53	43.19	25.81
9	51.78	19.22	60.17	22.39	39.95	14.62	39.81	16.64	25.87	12.32
10	100.04	26.80	98.10	25.84	91.54	24.82	79.37	25.41	173.79	68.95

APPENDIX C: INFORMED CONSENT STATEMENTS

Study #05-10319

INDIANA UNIVERSITY – BLOOMINGTON
INFORMED CONSENT STATEMENT

Investigation of the Max Power Model and the Velocity Perturbation Model for Assessing Resistive and Propulsive Forces in Swimming

You are invited to participate in a research study. The purpose of this study is to compare two different ways of measuring propulsive and resistive (or drag) forces of swimmers.

INFORMATION

The study will be made up of two parts of which you will be asked to participate in only one. You will choose the part of the study in which you participate. The first part of the study will compare the forces on individuals swimming front crawl in five different conditions: normal, wearing a drag suit with pockets, wearing a wetsuit, wearing hand paddles, and wearing gloves that hold the hand in a fist. The second part of the study will compare the forces on individuals swimming each of the four competitive strokes (butterfly, backstroke, breaststroke, and front crawl) and underwater dolphin kicking. The stroke in which you complete the testing will be your choice.

For each study your mass will be measured with a scale and your height will be measured with a stadiometer (which is similar to a meter stick). You will also be asked to provide your age and your best time from competition for 100 yards in the stroke you will be swimming. After this, you will be asked to warm up as you would like but with a minimum of 500 yards of total swimming. Next you will be tested for power output. You will be asked to swim two 22.5 m sprint. You will then be asked to swim between ten and twenty-five 13.5 meter maximal effort swim sprints while attached to a weight and pulley system. The weight and pulley system consists of a cable that is attached to your waist by a belt at one end and a weight stack outside of the water at the other end. Each of your swims will be with a different weight on the pulley system, beginning with no weight and then increasing. Finally, you will be asked to warm down at least 200 yards.

If you are participating in the first part of the study, you will be tested in three sessions. The first two sessions, you will be asked to complete two tests for power output and the final session you will be asked to complete one test for power output. The first two sessions in which you are tested will take approximately 1 hour and 15 minutes. The final session of testing will take approximately 45 minutes. In total, the three sessions will require about 3 hours and 15 minutes of your time. If you are participating in the second part of the study, you will be tested only once taking approximately 45 minutes.

A total of 100 subjects will be recruited for the study as a whole, with 10 taking part in the first part of the study and an addition 90 taking part in the second part of the study.

(Page 1 of 3)

RISKS

There is minimal risk in these tests. The power test is similar to sprint swimming in that you will be exerting a maximal amount of effort for a short period of time. You may feel fatigued or have sore muscles afterwards. As you are a trained swimmer, this is unlikely to occur and will be less likely with a properly completed warm up and warm down.

EMERGENCY MEDICAL TREATMENT

In the unlikely event of physical injury resulting from your participation in this research, emergency medical treatment will be provided at no cost to you. Be certain that you immediately notify the researcher if you are injured. If you require additional medical treatment you will be responsible for the cost. No other compensation will be provided if you are injured in this research.

BENEFITS

This study will be used to help make testing of propulsive and resistive (or drag) forces during swimming available to swimming coaches. This will help coaches to design better training and help swimmers improve more quickly. This research will also make it easier for scientists to study things that can make swimmers go faster including stroke technique and equipment such as swimming suits. Participating in the study may also help you by providing you with a small amount of swimming specific power training and information about your own skill level.

CONFIDENTIALITY

The information obtained by the study will be kept confidential. Your name will be stored separately from the data. The link between your name and the data collected will be kept in a locked file cabinet accessible only to the persons conducting the study. When the study is completed in August 2006, this link will be destroyed. Any results reported will not use your name.

CONTACT

If you have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study) you may contact the researcher, Joshua White, at HPER 112, 1025 E 7th St, Bloomington IN 47405, 812-856-7164, and jocwhite@indiana.edu.

If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the office for the Indiana University Bloomington Human Subjects Committee, Carmichael Center L03, 530 E. Kirkwood Ave., Bloomington, IN 47408, 812/855-3067, by e-mail at iub_hsc@indiana.edu.

Subject's Initials _______

(Page 2 of 3)

PARTICIPATION

Your participation in this study is voluntary; you may refuse to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be destroyed.

CONSENT

I have read this form and received a copy of it. I have had all my questions answered to my satisfaction. I agree to take part in this study.

Subject's signature____________________________ Date _________________

Consent form date: 3/3/2006

(Page 3 of 3)

Study #05-10319

INDIANA UNIVERSITY – BLOOMINGTON
INFORMED CONSENT STATEMENT

Investigation of the Max Power Model and the Velocity Perturbation Model for Assessing Resistive and Propulsive Forces in Swimming

Your child is invited to participate in a research study. The purpose of this study is to compare two different ways of measuring propulsive and resistive (or drag) forces of swimmers.

INFORMATION

The study will be made up of two parts of which your child will be asked to participate in only one. You and your child will choose the part of the study in which your child participates. The first part of the study will compare the forces on individuals swimming front crawl in five different conditions: normal, wearing a drag suit with pockets, wearing a wetsuit, wearing hand paddles, and wearing gloves that hold the hand in a fist. The second part of the study will compare the forces on individuals swimming each of the four competitive strokes (butterfly, backstroke, breaststroke, and front crawl) and underwater dolphin kicking. The stroke in which your child completes the testing will be his/her choice.

For each study your child's mass will be measured with a scale and your child's height will be measured with a stadiometer (which is similar to a meter stick). Your child will also be asked to provide his/her age and his/her best time from competition for 100 yards in the stroke your child will be swimming. After this, your child will be asked to warm up as he/she would like but with a minimum of 500 yards of total swimming. Next your child will be tested for power output. Your child will be asked to swim two 22.5 m sprints. Your child will then be asked to swim between ten and twenty-five 13.5 meter maximal effort swim sprints while attached to a weight and pulley system. The weight and pulley system consists of a cable that is attached to your child's waist by a belt at one end and a weight stack outside of the water at the other end. Each of your child's swims will be with a different weight on the pulley system, beginning with no weight and then increasing. Finally, your child will be asked to warm down at least 200 yards.

If your child is participating in the first part of the study, your child will be tested in three sessions. The first two sessions, your child will be asked to complete two tests for power output and the final session your child will be asked to complete one test for power output. The first two sessions in which your child is tested will take approximately 1 hour and 15 minutes. The final session of testing will take approximately 45 minutes. In total, the three sessions will require about 3 hours and 15 minutes of your child's time. If your child is participating in the second part of the study, your child will be tested only once taking approximately 45 minutes.

A total of 100 subjects will be recruited for the study as a whole, with 10 taking part in the first part of the study and an addition 90 taking part in the second part of the study.

Child's Initials _______
Parent's Initials _______

(Page 1 of 3)

RISKS

There is minimal risk in these tests. The power test is similar to sprint swimming in that your child will be exerting a maximal amount of effort for a short period of time. Your child may feel fatigued or have sore muscles afterwards. As your child is a trained swimmer, this is unlikely to occur and will be less likely with a properly completed warm up and warm down.

EMERGENCY MEDICAL TREATMENT

In the unlikely event of physical injury resulting from your child's participation in this research, emergency medical treatment will be provided at no cost to you or your child. Be certain that your child immediately notifies the researcher if he/she is injured. If your child requires additional medical treatment you will be responsible for the cost. No other compensation will be provided if your child is injured in this research.

BENEFITS

This study will be used to help make testing of propulsive and resistive (or drag) forces during swimming available to swimming coaches. This will help coaches to design better training and help swimmers improve more quickly. This research will also make it easier for scientists to study things that can make swimmers go faster including stroke technique and equipment such as swimming suits. Participating in the study may also help your child by providing him/her with a small amount of swimming specific power training and information about his/her own skill level.

CONFIDENTIALITY

The information obtained by the study will be kept confidential. Your child's name will be stored separately from the data. The link between your child's name and the data collected will be kept in a locked file cabinet accessible only to the persons conducting the study. When the study is completed in August 2006, this link will be destroyed. Any results reported will not use your child's name.

CONTACT

If you or your child have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study) you may contact the researcher, Joshua White, at HPER 112, 1025 E 7th St, Bloomington IN 47405, 812-856-7164, and _jocwhite@indiana.edu.

If you or your child feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the office for the Indiana University Bloomington Human Subjects Committee, Carmichael Center L03, 530 E. Kirkwood Ave., Bloomington, IN 47408, 812/855-3067, by e-mail at iub_hsc@indiana.edu.

Child's Initials _______
Parent's Initials _______

(Page 2 of 3)

PARTICIPATION

Your child’s participation in this study is voluntary; he/she may refuse to participate without penalty. If your child decides to participate, he/she may withdraw from the study at any time without penalty and without loss of benefits to which your child is otherwise entitled. If your child withdraws from the study before data collection is completed his/her data will be destroyed.

CONSENT

I have read this form and received a copy of it. I have had all my questions answered to my satisfaction. I agree to take part in this study.

Subject's signature____________________________ Date _________________

I agree to allow my child, ________________________, to take part in this study.

Parent's signature_____________________________ Date _________________

Consent form date: 3/3/2006

(Page 3 of 3)

Study #05-10319

INDIANA UNIVERSITY – BLOOMINGTON
INFORMED CONSENT STATEMENT

Investigation of the Max Power Model and the Velocity Perturbation Model for Assessing Resistive and Propulsive Forces in Swimming

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INFORMATION

The study will be made up of two parts of which you will be asked to participate in only one. You will choose the part of the study in which you participate. The first part of the study will compare the forces on individuals swimming front crawl in five different conditions: normal, wearing a drag suit with pockets, wearing a wetsuit, wearing hand paddles, and wearing gloves that hold the hand in a fist. The second part of the study will compare the forces on individuals swimming each of the four competitive strokes (butterfly, backstroke, breaststroke, and front crawl) and underwater dolphin kicking. The stroke in which you complete the testing will be your choice.

For each study your mass will be measured with a scale and your height will be measured with a stadiometer (which is similar to a meter stick). You will also be asked to provide your age and your best time from competition for 100 yards in the stroke you will be swimming. After this, you will be asked to warm up as you would like but with a minimum of 500 yards of total swimming. Next you will be tested for power output. You will be asked to swim between ten and twenty-five 12 meter maximal effort swim sprints while attached to a weight and pulley system. The weight and pulley system consists of a cable that is attached to your waist by a belt at one end and a weight stack outside of the water at the other end. Each of your swims will be with a different weight on the pulley system, beginning with no weight and then increasing. Finally, you will be asked to warm down at least 200 yards.

If you are participating in the first part of the study, you will be tested in three sessions. The first two sessions, you will be asked to complete two tests for power output and the final session you will be asked to complete one test for power output. The first two sessions in which you are tested will take approximately 1 hour and 15 minutes. The final session of testing will take approximately 45 minutes. In total, the three sessions will require about 3 hours and 15 minutes of your time. If you are participating in the second part of the study, you will be tested only once taking approximately 45 minutes.

A total of 100 subjects will be recruited for the study as a whole, with 10 taking part in the first part of the study and an addition 90 taking part in the second part of the study.

Subject's Initials _______

RISKS

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EMERGENCY MEDICAL TREATMENT

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Subject's Initials _______

PARTICIPATION

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CONSENT

I have read this form and received a copy of it. I have had all my questions answered to my satisfaction. I agree to take part in this study.

Subject's signature___________________________ Date _________________

Consent form date: 8/29/2005

3745 N Hinkle Rd
Bloomington, IN 47408
(812) 322-1896
jocwhite@indiana.edu

Joshua C. White

HPER 112
1025 E 7th St
Bloomington, IN 47405
(812) 856-7164

Education

Indiana University	PhD Candidate (expected completion Aug 2006)
Major: Human Performance (Ex. Phys)	Minor: Physiology
Kenyon College	BA May, 2001
Major: Physics	Minor: Math

Research

Research Experience:

Associate Instructor Indiana University School of HPER (2001-Present)

- Researcher for the Counsilman Center for the Science of Swimming
  - Studied competitive swimming starts on a grant from USA Swimming ($82,802)
    - Developed experimental design and equipment
    - Collected data
    - Presented data to funding agency
    - Coauthored grant renewal of $69,421
  - Studied power generation during swimming and its relation to propulsive and drag forces
  - Aided in data collection for a study of the maturation of competitive swimmers on a grant from USA Swimming ($25,000)

Grant Supported Researcher Indiana University (Summer 2004, 2005)

Summer Research Assistant Indiana University (2002, 2003)

Summer Science Scholar, Kenyon College (2000)

- Created a computer program in Java to mathematically and graphically model tree branching patterns using L-system mathematics with an added element of randomness

Participant in Research Experience for Undergraduates in Nanostructured Materials at University of Nebraska (1998)

- Did guided independent research into the ferroelectric switching of thin films culminating in the presentation of results in written and auditory forms

Grants:

Funded

Stager, J.M. & White, J.C. *USA Swimming*. "Underwater Analysis of the Competitive Swimming Start: Part II." ($69,421). December, 2005.

Submitted - Unfunded

Stager, J.M. & White, J.C. *USA Swimming Competitive Non-Restricted Grant.* "Investigation of Resistive and Propulsive Forces in Swimming." ($11,992). September, 2005.

Stager, J.M. & White, J.C. *USA Swimming Competitive Non-Restricted Grant.* "Maximum Power and Resistance Forces during Swimming." ($14,707). September, 2004.

Publications:

White, J.C., Stager, J.M., Parry, T.E., Willmott, A.P, Cornett, A.C. (2006). Ability of competitive swimmers to modify start depth is not dependent upon experience. J.P. Vilas-Boas, F. Alves, A. Marques (eds.), Book of Abstracts of the Xth International Symposium Biomechanics and Medicine in Swimming. *Portuguese Journal of Sport Sciences, Suppl 1*, 2006. (in print). (Abstract to be presented as a poster)

White, J.C. & Stager, J.M. (2004). The relationship between drag forces and velocity for the four competitive swimming strokes. *Medicine and Science in Sports and Exercise, 36*, S9. (Abstract presented orally)

White, J.C., Stager, J.M., Tanner, D.A., Simmons, S.E.C., & Naganobori, H. (2003). Approximation of active drag forces during freestyle swimming using values of velocity, force, and power. *Medicine and Science in Sports and Exercise, 35*, S97. (Abstract presented as a poster)

Wright, B.V., White, J.C., Parry, T.E., Willmott, A.P., Nelson, C.S., Cornett, A.C., & Stager, J.M. (2005). Maximum Hand, Head, Knee, and Toe Depths During the Competitive Swimming Start Differ with Race Distance. Medicine and Science in Sports and Exercise, 37, S122-S123. (Abstract presented as a poster)

Simmons, S. E., White, J.C., & Stager, J.M. (2004). Maturity Assessment in Competitive Swimmers. *Medicine and Science in Sports and Exercise, 36*, S103. (Abstract presented as a poster)

Teaching

Teaching Experience:

Associate Instructor Indiana University School of HPER (2001-Present)
- ◦ Instructor of exercise physiology, personal fitness, and swimming courses

Physics Tutor Kenyon College (1999)

Coaching

Coaching Experience:

Volunteer Coach Indiana University Men's Team (2002-2005)
- ◦ Athletes Coached
  - ◦ World Championship Silver Medalist (800 Freestyle Relay)
  - ◦ World University Games Silver Medalist (100 Breaststroke)
  - ◦ Numerous NCAA DI and Olympic Trial Qualifiers
- ◦ Team Places
  - ◦ Big Ten Conference: 3rd 2003, 4th 2004, 2nd 2005
  - ◦ NCAA: 21st 2003, 17th 2004, 16th 2005

Swimming Camp Researcher and Lecturer
- ◦ Total Performance Elite Sprint Camp (2002, 2004, 2005)
- ◦ Indiana Swim Camp (Lecturer Only) (2004, 2005)
- ◦ Indiana Science of Swimming Camp (Researcher Only) (2003)
- ◦ Delivered lectures on nutrition, metabolism, and swimming power training
- ◦ Collected predictive measurements of sprint performance and produced reports for camp participants

Assistant Coach
- ◦ Indiana Swim Team (2002-2005)
- ◦ Bloomington Swim Club (Summer 2002)

- ◦ Bloomington High School South (2001-2002)

Swimming Lesson Program Supervisor

- ◦ Offutt Air Force Base Youth Services (1997-1998)
- ◦ Bellevue Swim Club (1998)
- ◦ Responsible for hiring, personnel management and day to day operations

Swimming Experience:

NCAA Competitor (Kenyon College): 4 years

- ◦ 3 time Qualifier NCAA Div III National Meet
- ◦ NCAA D-III Swimming All-American (1 time individual, 2 time relay) (2000)
- ◦ NCAA D-III Swimming All-American Honorable Mention (3 time) (2000,2001)
  - ◦ Highest Individual Finish: 7th 200 Freestyle (2000)
  - ◦ Highest Relay Finish: 1st 800 Freestyle Relay (1999, 2000)
  - ◦ Highest Team Finish: 1st 1998, 1999, 2000, 2001

USA Swimming Competitor (Swim Omaha): 12 years

- ◦ Junior National Qualifier

High School Competitor (Bellevue West HS): 4 years

- ◦ Nebraska High School State Champion 500 Freestyle 1996

Honors

Swimming:

Verizon Academic All-American First Team (2001)
North Coast Athletic Conference Scholar-Athlete Award (2000-2001)
NCAA D-III Academic-All American Swimming Team (1999-2001)
Swimming Coach’s Award Winner (1999)

Academic:

Chair of IU School of HPER Graduate Student Advisory Council (2003-2005)
School of HPER University Scholarship from Indiana University (2001-2005)
Swift-Russell Scholarship IU Department of Kinesiology (2003-2004)
Updyke/President’s Challenge Fellowship IU School of HPER (2001-2003)
Kenyon College Class of 2001 Salutatorian
Phi Beta Kappa Member (2000)
Kenyon College Honor Scholar (1997-2001)
Kenyon College Merit List (1997-2001)
