THE ROLE OF UPPER BODY POWER IN CLASSICAL

CROSS-COUNTRY SKIING PERFORMANCE

by

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ABSTRACT

The purpose of this study was to evaluate the relationship between upper body power (UBP) and classical cross-country ski race performance. A group of experienced skiers (7 men, 3 women) completed 3 laboratory tests of UBP on a custom-built double poling ergometer: a 10-second test, a 60-second test, and an incremental test to exhaustion lasting 240-630 seconds. All subjects also competed in the West Yellowstone NorAm race on November 26, 2004. Unfortunately, the small subject number precluded any significant analysis of these data. A second group of skiers (10 men, 5 women) completed the same laboratory testing procedure and competed in the West Yellowstone Spam Cup race on December 11, 2004. Pearson's product-moment correlation coefficients were calculated between average race speed (RS) and average 10-second power output (W_{10}), average 60-second power output (W_{60}), peak power output achieved during the incremental test (W_{peak}), and peak oxygen uptake during the incremental test (VO_{2peak}). After removal of 2 male subjects from the analysis, all 4 measures were found to correlate significantly with RS (r = .73-.95). W_{peak} relative to bodyweight showed the highest correlation with RS (r = .95). When data was analyzed separately by gender, relative W_{10} was the best predictor of RS for women (r = .96) and absolute W_{10} was the best predictor of RS for men (r = .90). W_{10} and W_{60} were highly correlated with W_{peak} for all subjects in both groups (r = .96 and .97, respectively). Regression analysis also indicated that a 5% improvement in relative W_{peak} could decrease race time by as much as 39 seconds in a 10-km classical race. These findings suggest that both long and short term UBP are important for classical race performance, and that the factors determining short term UBP may be identical to those determining long term UBP.

CHAPTER ONE

INTRODUCTION

The sport of cross-country skiing is thought to have originated over 4000 years ago in northern Europe (Clifford, 1992). The oldest pair of skis discovered dates back to 2500 BC, while the oldest known description of the sport is a cave painting in Rodoy, Norway, from 2000 BC. Written accounts as early as 551 AD describe skiing as a utilitarian rather than recreational activity, necessary for travel, hunting, and battle in the snow-covered lands north of the Arctic Circle. Only after thousands of years did skiing become a competitive sport. A troop of Norwegian soldiers held the first recorded ski competition in 1767. Ski racing gradually became popular throughout Scandinavia, finally spreading to the rest of the world in the 1890s. In 1924, cross-country ski racing was an event at the first Winter Olympics in Chamonix, France.

For the better part of the 20th century, cross-country ski racing consisted only of the classical style, in which the skis remain parallel to each other. In this style of skiing, the skier strides uphill by springing from one ski to another while pushing with the opposing pole in a motion similar to running. The double pole technique is used while classical skiing in flat terrain; the skier pushes on both poles simultaneously while bending slightly at the waist, which allows assistance by the trunk muscles. By the mid-1980s, a new skiing style called “skating” had become popular in cross-country ski racing. Ski-skating is a motion similar to ice skating: the skis are turned outward in a V shape, and the skier moves laterally from ski to ski while pushing with both poles. Today, skating and classical races are held as separate events, and most racers participate in both events. Although the two styles appear quite different, they require the same fitness components for success: balance, coordination, aerobic and anaerobic endurance, and upper body power (Saltin, 1997).

The need for upper body power (UBP) in cross-country ski racing is a consequence of the use of poles for propulsion. Power generated by the upper body is transmitted through the poles and assists in forward motion. As discussed previously, the upper body is the sole source of power during classical double poling. The upper body may also contribute as much as 50% of the propulsive force during uphill skating (Street, 1989) and 15% to 30% during uphill classical skiing (Komi, 1987).

Numerous researchers have attempted to determine the best method of developing UBP in cross-country skiers (Downing & Wilcox, 2003; Hoff, Gran, & Helgerud, 2002; Hoff, Helgerud, & Wisloff, 1999; Nesser, Chen, Serfass, & Gaskill, 2004; Nilsson, Holmberg, Tveit, & Hallen, 2004; Osteras, Helgerud, & Hoff, 2002). Results of these studies indicate that ski-specific strength training methods are highly effective; however, none offer any indication as to whether training for short or long term UBP is more effective for improving race performance. Also, the extent to which UBP influences racing success is not entirely clear. Several researchers have concluded that UBP plays an important role in race performance (Gaskill, Serfass, & Rundell, 1999; Heil, Engen, & Higginson, 2004; Mahood, Kenefick, Kertzer, & Quinn, 2001; Rundell, 1995; Rundell & Bacharach, 1995; Staib, Im, Caldwell, & Rundell, 2000). However, the definition of "upper body power" varies widely between studies, and only Staib et al. (2000) have attempted to differentiate between short and long term UBP. Further, classical race performance is largely unrepresented in this body of research; all of these studies use either skating races only or a combination of skating and classical races to define the performance variable. To date, no study has attempted to evaluate the relationship between classical ski race performance and ability to generate upper body power over short and long time periods. The answer to this question could provide useful insight into appropriate upper body power training methods for cross-country skiers.

Statement of Purpose

The purpose of this study was to determine the relationship between UBP and classical cross-country ski race performance. This was accomplished by comparing average classical race speed to four laboratory based measures of UBP and oxygen uptake: average power output in a 10-second test (W_{10}), average power output in a 60-second test (W_{60}), peak power output achieved during an incremental test to exhaustion (W_{peak}), and peak oxygen uptake during the incremental test to exhaustion (VO_{2peak}). The ensuing analysis determined whether any of the dependent measures correlated significantly to classical ski race performance.

Hypothesis

All four laboratory measures (W_{10}, W_{60}, W_{peak}, and VO_{2peak}) will correlate positively with classical cross-country skiing speed.

$$\mathbf{H_0:\ \mu_r \leq 0}$$

$$\mathbf{H_A:\ \mu_r > 0}$$

where μ_r is the population average correlation between classical ski race performance (independent variable) and one of several measures of upper body power (dependent variables).

Limitations

1. Poles used on the double poling ergometer were available in lengths from 135 to 170 cm in 5-cm increments. Some skiers had to use poles slightly longer or shorter than their preferred length.
2. Many external factors may affect race performance, including ski and pole selection and ski base preparation (e.g. waxing). The present study lacked the resources to control for these factors.

Assumptions

1. It was assumed that measures of UBP obtained on the ergometer were truly representative of UBP during classical double poling.
2. It was assumed that each skier's race performance was a maximal effort, with no intent to use the race as a training session for future races.

Delimitations

1. The scope of this study was delimited to experienced cross-country ski racers from Bozeman, Montana.

Operational Definitions

Maximal Oxygen Uptake (VO_{2max}):	The maximal rate of oxygen utilization by working muscles during exercise. Maximal oxygen uptake varies depending on the mode of exercise, and is generally highest during running. Therefore, a maximal oxygen uptake measure obtained during another mode of exercise is sometimes referred to as "peak oxygen uptake," or VO_{2peak}.
Respiratory Exchange Ratio (RER):	The ratio of the rate of CO_2 exhalation to the rate of O_2 consumption (VCO_2/VO_2).
Work Economy:	The rate of energy expenditure (as represented by oxygen consumption) required to accomplish a given task.
Classical Style:	The traditional manner of cross-country skiing, which involves striding from ski to ski while pushing with the opposing pole. The skis remain parallel to each other.
Skating Style:	A method of cross-country skiing in which the skis are aligned in a V shape, with tips pointed outward. The skier pushes laterally from ski to ski in a manner similar to ice skating, while pushing with both poles simultaneously.
Double Poling:	Pushing with both poles simultaneously during cross-country skiing. In the classical style, double poling is often used as the sole propulsive force, with no assisting push from the legs. In the skating style, double poling is coordinated in conjunction with leg pushes.
Upper Body Power:	The rate at which work can be performed using the arm, shoulder, and trunk muscles.

CHAPTER TWO

REVIEW OF THE LITERATURE

Introduction

Power is defined as the rate of work production, or the speed at which a given force is applied. The sport of cross-country skiing requires power to be applied to the poles using the arm, shoulder, and trunk muscles. The ability to apply power during poling is typically referred to as upper body power (UBP). Prior research on UBP in cross-country skiing can be divided into two categories: observational studies, in which the relationship between UBP and race performance is evaluated, and training studies, in which different methods of UBP training are tested experimentally.

Energy Systems for Power Production

Upper body power studies have used tests of varying duration to measure UBP. However, most observational research has not attempted to compare the importance of short term UBP to long term UBP. Only Staib et al. (2000) have attempted to identify the relative importance of short and long term UBP to race performance by comparing UBP tests of different duration.

The distinction between short and long term tests of UBP is important because different metabolic systems provide energy for actions of different durations. The energy required for muscular power production comes from the splitting of adenosine triphosphate (ATP), which can be generated by three different metabolic pathways: the

ATP-phosphocreatine (PCr) system, the glycolytic system, and the oxidative system (Gastin, 2001). The ATP-PCr and glycolytic system are often referred to as the "anaerobic system," because neither requires oxygen to generate ATP. The ATP-PCr system generates energy by splitting PCr, while the glycolytic system provides energy through the breakdown of glycogen without oxygen. The ATP-PCr system provides most of the energy for the first 5-10 seconds of maximal exercise, after which its ATP production declines rapidly. As the contribution of the ATP-PCr system decreases, the glycolytic system gradually becomes the dominant energy system for actions lasting from 10-75 seconds. The oxidative (aerobic) system generates ATP through the breakdown of glycogen in the presence of oxygen, and is thought to provide most of the energy for actions lasting longer than 1-2 minutes. Both anaerobic and aerobic systems are thought to provide energy for virtually any action, regardless of duration; however, the anaerobic system is dominant for short term actions (less than 1-2 minutes), while the aerobic system provides the majority of energy needed for longer actions. Thus, it would seem logical that a test of anaerobic UBP should be less than 2 minutes in length to avoid a large energy contribution from the aerobic system.

Observational Studies

Numerous studies have identified UBP as an important determinant of cross-country ski race performance (Gaskill et al., 1999; Heil et al., 2004; Mahood et al., 2001; Rundell, 1995; Rundell & Bacharach, 1995; Staib et al., 2000). One of two methods is typically used to evaluate UBP: criterion measures of UBP, such as a double poling time trial on rollerskis, or direct measurement of power output on an arm ergometer.

Performance has typically been defined as average speed or finish time for one or more rollerski or on-snow races or time trials. Points systems based on an entire season of races have also been used. All prior UBP studies have observed skating events as a performance measure, with one exception: Staib et al. (2000) used race points derived from several races of both styles as a performance measure. A few studies have directly compared upper body power or strength with maximal oxygen uptake (VO_{2max}) determined by running or rollerskiing as a measure of lower or whole body fitness (Mahood et al., 2001; Ng et al., 1988; Rundell & Bacharach, 1995). In all cases, upper body fitness measures have been found to be slightly better predictors of performance.

Upper body power appears to predict performance for a wide range of subgroups, as shown by Gaskill et al. (1999). In this study, researchers found a strong relationship ($r = .89$) between peak power output in Watts (W) achieved on an arm ergometer and average race speed among a heterogeneous group of 158 skiers. The ergometer required subjects to pull on cables to simulate a double poling motion. Peak power output was determined by an incremental test to exhaustion lasting 3-6 minutes. Average race speed was calculated from past skating races completed by the subjects. The authors concluded that approximately 70% of the variance in race speed among a heterogeneous group of skiers could be accounted for by variance in UBP. Even when the groups were sorted according to gender and skill level, UBP still accounted for 32 to 34% of race speed variance.

Rather than measure UBP directly using an ergometer, Mahood et al. (2001) used a double poling time trial as a criterion measure of UBP. They measured several physiological variables in a group of male collegiate skiers to determine which best predicted performance in a 10-km skating race on rollerskis. Time to complete a 1-km double poling time trial proved to be the best predictor of race performance (r = .92), ahead of maximal oxygen uptake during skiing (VO_{2peak}), oxygen uptake (VO_2) at lactate threshold, and skiing economy. Like the UBP test used by Gaskill et al. (1999), the double pole time trial lasted several minutes, with a mean time of 229 seconds.

Two studies have focused on UBP in elite biathletes (the sport of biathlon combines ski-skating with target shooting). Rundell and Bacharach (1995) found a high correlation (r = -.84) between performance on a 1-km uphill double pole time trial on snow and United States Biathlon Association (USBA) points among elite male biathletes. The same study also found a strong relationship (r = -.95) between USBA points and peak UBP (W) during an incremental test to exhaustion (using an arm ergometer) among female, but not male, biathletes. In a similar study, Rundell (1995) found a high correlation (r = -.85) between time to complete a 15-km biathlon race (not including shooting time) and peak UBP (W) in an identical arm ergometer test among female biathletes.

Only one observational study has attempted to differentiate between aerobic (long term) and anaerobic (short term) UBP (Staib et al., 2000). Aerobic UBP was evaluated by measuring peak oxygen uptake (VO_{2peak}) and time to exhaustion during an incremental treadmill test while double poling on rollerskis. Anaerobic UBP was defined as peak UBP (W) achieved during an incremental test similar to that used by Gaskill et al. (1999). A significant relationship was found between International Ski Federation (FIS) ranking points and VO_{2peak} (r = -.74) and time to exhaustion (r = -.80). Peak UBP was also a significant predictor of FIS points (r = -.68). The authors concluded that aerobic UBP, as evaluated by a test to exhaustion with a mean time of 848 seconds, was a slightly better predictor of performance than anaerobic UBP, as measured by the shorter peak UBP test (100-322 seconds). It should be noted that 75 seconds is thought to be the point at which anaerobic and aerobic energy systems provide equal amounts of energy for muscular work (Gastin, 2001); thus, the validity of this study's peak UBP test as a measure of anaerobic UBP is debatable.

A more short term measure of UBP was recently developed by Heil et al. (2004). Like Gaskill et al. (1999), researchers used an arm ergometer to measure UBP; however, the ergometer was modified such that subjects pushed on actual ski poles rather than pulling on cables. Subjects were instructed to gradually increase power output for the first 5 seconds of the test before poling with maximal effort for the remaining 10 seconds. Upper body power was calculated as the highest average power output over any 5-second period. Relative peak UBP ($W \cdot kg^{-1}$) achieved by a group of junior skiers was found to correlate highly with race time in a five-kilometer skating race ($r = -.88$), indicating that the ability of the upper body to generate power rapidly over a short time period may be an important factor in race performance, regardless of whether that power output can be sustained for several minutes.

Training Studies

Recent experimental research has attempted to determine the most effective training methods for developing UBP. A series of studies has focused on maximal strength training (high resistance, low number of repetitions), seeking to provide an alternative to the traditional approach of low resistance, high repetition strength training programs (Hoff et al., 2002; Hoff et al., 1999; Osteras et al., 2002). These studies tested a traditional training program against a maximal strength training program using a single exercise that closely imitated a ski poling motion. The maximal strength program resulted in far greater improvement in a double poling endurance test than did the traditional program. The maximal strength group also showed significant gains in double poling economy. The authors suggested that because the subjects had increased their maximal strength, they performed each double poling motion at less relative cost than their weaker counterparts, and consequently performed better in the double poling test.

Another possibility for the increase in double poling economy, the authors suggested, was a decrease in time to peak force in the experimental group (Hoff et al., 1999). In other words, these subjects experienced an increase in the contraction speed of their muscles, and were able to generate more power by increasing their rate of force production. The authors proposed that a quicker contraction meant that, in the course of one double pole stroke, muscle groups spent less time working (contracting) and more time resting. The final study in this series identified an increase in subjects' actual movement velocity as another mechanism behind an increase in double poling economy (Osteras et al., 2002).

Achieving high movement velocity would seem to be more difficult during high resistance motions such as those used in maximal strength training. However, Behm and Sale (1993) found that movement through a range of motion at a high velocity was not necessary to improve a muscle's rate of force production. In this study, subjects trained one leg using an isokinetic device that allowed ankle dorsiflexion at a high velocity, while the other leg was trained isometrically, by attempting ankle dorsiflexion against an immovable force. Subjects were required to attempt high velocity contractions during isometric exercise. The isometric training was found to be as effective as the isokinetic training at increasing rate of force production during ankle dorsiflexion, leading the authors to conclude that the attempt to move at a high velocity, rather than the actual movement itself, was the primary stimulus for improved neuromuscular ability to produce force rapidly. The authors proposed that high resistance training programs might be superior to high velocity exercises for developing muscular power.

In the wake of such findings, many elite ski programs have begun to use heavy weight training as a means of increasing maximal strength. However, it is not clear whether weight lifting exercises are as effective at improving UBP during double poling as the highly specific exercise used in recent maximal strength training studies (Hoff et al., 2002; Hoff et al., 1999; Osteras et al., 2002). The only study to directly compare weight training with ski-specific strength training seems to indicate that specific training is superior for developing UBP (Nesser et al., 2004). However, this study suffered from a high rate of attrition in the weight training group. The study also used a mix of maximal and sub-maximal training, simultaneously attempting to develop power, endurance, and strength in the upper body. Whether or not maximal weight training can effectively develop UBP for cross-country ski performance remains unclear.

Other studies have focused on comparisons of similar ski-specific training methods. Downing and Wilcox (2003) compared rollerboard and wind machine training programs. A rollerboard is a wheeled board that rolls up and down an inclined ramp; subjects lie on the board and pull themselves up the ramp with a pair of ropes. A wind machine consists of a set of rotating paddles which turn like a fan when a pair of ropes is pulled, providing resistance. Both devices allow a motion similar to double poling on skis. Investigators found that both methods were equally effective at improving UBP; however, the rollerboard group appeared to have achieved higher power by increasing force output, while the wind machine subjects increased their rate of force generation. Unfortunately, no data were collected to determine which method resulted in superior race performance.

Another ski-specific training study compared the effects of 20-second and 180-second double poling intervals on a variety of upper body parameters, including peak and mean UBP, lactate concentration during submaximal double poling, VO_{2peak}, and work economy (Nilsson et al., 2004). Both training programs resulted in many significant gains, but in different variables. The 20-second group showed greatest improvement in peak and mean power in a 30-second test and in work economy. The 180-second group improved in mean power in a 6-minute test, VO_{2peak}, and lactate concentration during submaximal double poling. This group also made gains in mean and peak 30-second power and work economy, but not as large as those of the 20-second group. Like Downing and Wilcox (2003), the authors concluded that both training methods were effective at increasing double poling ability, but made no attempt to determine which was superior for improving race performance.

Summary

Although no consensus exists as to the most effective method of developing UBP among cross-country skiers, recent studies have made progress toward identifying ideal UBP training methods. However, although several studies have found significant relationships between UBP and cross-country ski race performance, there is little evidence to suggest whether long or short term upper body power is a more important determinant of performance. Finally, the relationship between UBP and classical ski race performance alone has never been evaluated. The current study will attempt to determine which upper body parameters best predict classical race performance by comparing results of both short term (60 seconds or less) and long term (longer than 60 seconds) laboratory measurements of UBP to performance in an actual competition.

CHAPTER THREE

METHODOLOGY

Subjects

Twenty-two cross-country ski racers (15 men, 7 women) from Bozeman, Montana, volunteered to participate in this study. Subjects had the choice of competing in one or two classical style races as part of the study: the West Yellowstone NorAm race (12-km for men, 6-km for women), held on November 26, 2004, or the West Yellowstone Spam Cup race (10-km for all competitors), held on December 11, 2004. Thirteen subjects (9 men, 4 women) volunteered to compete in the NorAm race, and 19 subjects (13 men, 6 women) volunteered to compete in the Spam Cup race. Eleven subjects (8 men, 3 women) participated in both races. All subjects were between the ages of 18 and 42, with a minimum of 3 years of experience as nordic ski racers. Subjects read and signed an approved informed consent document explaining the requirements and potential risks of participation in the study (Appendix A).

Procedures

Testing

Participation in the study required three visits to the Montana State University Movement Science Laboratory in Bozeman, Montana. On the first visit, relevant descriptive information (age, height, and weight) was recorded, and subjects completed three trials of a 10-second test and a single 60-second test on a custom-built double poling ergometer. Subjects completed an incremental test to exhaustion on the ergometer during the second visit. Subjects were instructed to avoid any strength training or high intensity exercise for 48 hours prior to either testing session. The first two visits took place within 3-29 days of the subject's chosen race, and a minimum of 2 days apart from each other. On the final visit, each subject's body composition was estimated using hydrostatic weighing. Due to an equipment malfunction, the weighing process was not able to be conducted until approximately 4 months after the races for all subjects. Body composition was included as a descriptive measure only, and was not included in any further analyses.

10- and 60-Second Tests. After a 5-minute warm-up on the double poling ergometer at a power output of each subject's choice, subjects rested for 3 minutes before performing three consecutive trials of a 10-second test. Subjects were instructed to gradually increase their power output for 20 seconds before poling at maximal effort for the remaining 10 seconds. Subjects were encouraged to use the first trial as a warm-up, using 80% of maximal effort, before giving 100% effort on the final two trials. A 3-minute rest period was allowed between trials. The highest average power output achieved during the final 10 seconds was used as a measure of 10-second power output (W_{10}, W). Subjects then rested for 5 minutes before performing a single 60-second test, in which they attempted to achieve the highest average power output over 60 seconds (W_{60}, W) when starting from a dead stop.

Previous laboratory testing has established the reliability of these tests (unpublished data). Eight subjects (six men, two women) performed the protocol described above on two occasions separated by 2-14 days. Mean values for W_{10} and W_{60} across the first (Mean ± SE: 208.1 ± 21.0 W and 164.4 ± 15.5 W, respectively) and the second tests (210.4 ± 21.6 W and 161.8 ± 15.5 W, respectively) did not differ significantly ($P = 0.55$ and 0.39, respectively). Intraclass correlations were high for both W_{10} and W_{60}, whether computed across two rounds of measurement ($R_{xx} > .99$) or extrapolated for a single measurement ($R_{xx} > .98$). Standard error of measurement was ± 2.7 W (95% confidence interval: ± 5.4 W) for W_{10} and ± 2.0 W (95% confidence interval: ± 3.9 W) for W_{60}.

Incremental Test to Exhaustion. After a warm-up period identical to that used during the previous lab visit, subjects performed an incremental test to exhaustion on the double poling ergometer while oxygen uptake (VO_2) and heart rate (HR) were measured. Starting at 30 W for women and 40 W for men, work rate was increased by 15 and 20 W, respectively, every minute. The test ended when the subject's power output dropped 5 W or more below the required work rate for 5 seconds or more. The test was designed to last approximately 4-12 minutes. Peak oxygen uptake (VO_{2peak}) was defined as the point at which two or more of the following criteria were met: 1) A respiratory exchange ratio (RER) greater than 1.1; 2) A plateau in oxygen uptake, observed when the two highest VO_2 measurements were within 2.5 $ml \cdot kg^{-1} \cdot min^{-1}$ of each other; 3) A maximal HR within 10 beats of age-predicted maximum. The highest HR recorded during the test was considered the subject's maximal heart rate (HR_{max}). Peak power output (W_{peak}, W) was calculated using the following equation (Kuipers, Verstappen, Keizer, Geurten, & van Kranenburg, 1985):

$$W_{peak}\ (W) = W_{com} + (t/60) \times \Delta W \qquad (1)$$

Where W_{com} is the power output (Watts) of the last completed stage, t is the number of seconds completed in the last uncompleted stage, and ΔW is the change in power output of the last uncompleted stage.

Hydrostatic Weighing. Subjects sat on a chairlike in a tank full of water wearing a close-fitting swimsuit. The chair hung from a scale attached to the ceiling above the tank. The subjects exhaled as much air as possible before submerging themselves and remaining underwater for 8-12 seconds. At this time, the investigator recorded the scale's reading. This process was repeated four to eight times per subject and the highest stable weight was recorded. Underwater weight was used to estimate body density. The prediction equation developed by Siri (1956, p. 14) was used to calculate percent body fat from body density for men, and an equation recommended by the American College of Sports Medicine (2000, p. 62) for white women ages 20-80 was used to calculate percent body fat for women.

Racing

Subjects were responsible for their own entry fees, equipment, and transportation to and from the races. Specific pre-race procedures (e.g. eating, warm up, waxing) were of the subjects' choosing. Average race speed was calculated by dividing the course distance by each subject's race time.

The Spam Cup and NorAm races used a 6-km race course (the second lap of the Spam Cup race cut off part of the loop to make the total race distance10 km). The high and low points on the course were approximately 2040 and 2090 m, respectively. The course followed varied terrain, with frequent climbs and descents, but few climbs lasting longer than 100 m. The longest sustained climb gained 25 m of elevation over 500 m. Most racers reported using the double pole technique for one-half to two-thirds of the race, although a few of the stronger racers reported double poling roughly three-fourths of the race.

Instrumentation

A modified Concept 2 Model D rowing ergometer (Concept 2, Morrisville, VT, USA), similar to that described by Nilsson et al. (2004), was used for all testing in this study (Figure 1). This ergometer had a longer steel rail than a typical rowing ergometer. Subjects stood on a wooden platform mounted to the front of the rail. In place of the sliding seat on a typical Concept 2 ergometer, a resistance-loaded trolley was connected to a chain that turned an air-braked flywheel. A pair of cross-country ski poles was attached to the trolley. Pushing on the poles made the trolley slide backward along the rail. The chain then turned the flywheel, thus providing resistance. The ergometer gave a continuous reading of power output in Watts, and also recorded average power output over a given work period. The power measurements of the Concept 2 ergometer have been shown to be reliable in test-retests lasting approximately 90 seconds and 420 seconds (Soper & Hume, 2004). Research on the validity of the Concept 2 ergometer's power measurements has not been published.

Figure 1. Photo of the double poling ergometer.

The poles attached to the ergometer were removable, allowing subjects to choose poles of their preferred length. Poles were available in lengths from 135 cm to 170 cm in 5-cm increments; thus, some subjects had to use poles that were slightly longer or shorter than their normal preferred pole length. All poles used in this study were Toko P232 poles (Mammut Sports Group AG, Seon, Switzerland) with Infinity synthetic cork grips and Infinity Vise straps (Zaveral Racing Equipment, Mt. Upton, NY, USA).

Oxygen uptake during the test to exhaustion was measured by a TrueMax 2400 Analyzer Module (Parvo Medics, Sandy, UT, USA). Subjects breathed room air through a mouthpiece fitted with one-way valves, which directed expired air into the analyzer module via a length of plastic tubing. Certified gas mixtures were used to calibrate the oxygen and carbon dioxide analyzers. Ventilation measurements were checked using a calibrated 3-liter syringe (Hans Rudolph, Kansas City, MO, USA). Oxygen uptake was calculated every 20 seconds during the incremental test. Heart rate was continuously monitored by a Polar Accurex Plus heart rate monitor (Polar Electro, Inc., Lake Success, NY, USA), with an average HR recorded every 5 seconds.

Analysis

Upper body VO_{2peak}, W_{peak}, W_{10}, and W_{60} were correlated with average race speed using Pearson product-moment correlation coefficients and Fischer's *Z* transformation to calculate 95% confidence intervals. Simple linear least-squares regression procedures were also used to predict classical race speed from the independent variables. All statistical evaluations were performed at the .05 alpha level using the Statistical Package for the Social Sciences software, version 12.0 (SPSS Inc., Chicago, IL, USA). Data were analyzed separately for each gender, and for the entire group of subjects in the Spam Cup race. Due to different race distances for men and women in the NorAm race, these data could only be analyzed separately by gender. Using the procedures outlined by Cohen (1988), a sample size of at least eight skiers was required to detect a correlation of .75 or more at a power of .80 and alpha of .05.

CHAPTER FOUR

RESULTS

The purpose of this study was to evaluate the relationship between upper body power (UBP) and classical cross-country ski race performance. Upper body power testing was performed on a double poling ergometer and involved three tests: a 10-second test, a 60-second test, and an incremental test to exhaustion. Four measures were drawn from these tests: average power output in the 10- and 60-second tests (W_{10} and W_{60}, respectively), peak power output achieved during the incremental test (W_{peak}), and peak oxygen uptake during the incremental test (VO_{2peak}). Subjects participated in one or two classical style races as a performance measure: the West Yellowstone NorAm SuperTour race (6-km for women, 12-km for men), or the West Yellowstone Spam Cup race (10-km for all racers).

Thirteen subjects (9 men, 4 women) volunteered to participate in laboratory testing and compete in the NorAm race. However, only 10 subjects (7 men, 3 women) competed in the race. Subject attrition was due to the fact that very little snow fell in the Bozeman area in the weeks prior to the race, and most local skiers were unable to spend much time skiing on snow to prepare for the race. Many subjects felt uncomfortable with attempting the race with limited on-snow training, and thus withdrew from the study after laboratory testing. Age, height, weight, and % body fat of the 10 racers are summarized in Table 1.

Table 1. NorAm subject characteristics (Mean ± SD).

	n	Age (years)	Height (cm)	Weight (kg)	% Body Fat
Men	7	21.6 ± 3.7	183.6 ± 7.4	77.3 ± 8.3	10.0 ± 3.8
Women	3	20.3 ± 1.5	166.8 ± 5.8	57.9 ± 4.2	13.1 ± 5.2

Since NorAm race distances were different for men and women, data for this part of the study could only be analyzed separately by gender. Speed averaged during the NorAm race (RS) was 4.69 ± 0.17 $m \cdot s^{-1}$ for women and 5.31 ± 0.38 $m \cdot s^{-1}$ for men (Mean ± SD). Tables 2 and 3 summarize the results from the four laboratory measures. All measures are presented as absolute and relative to body mass.

Table 2. Results of 10- and 60-second tests of upper body power – NorAm subjects (Mean ± SD).

	n	W_{10} (W)	W_{10} ($W \cdot kg^{-1}$)	W_{60} (W)	W_{60} ($W \cdot kg^{-1}$)
Men	7	274.6 ± 42.8	3.55 ± 0.44	209.7 ± 28.9	2.71 ± 0.23
Women	3	158.7 ± 24.8	2.73 ± 0.26	126.7 ± 22.8	2.18 ± 0.27

W_{10} = power output from 10-second test; W_{60} = power output from 60-second test.

Table 3. Results of incremental test to exhaustion – NorAm subjects (Mean ± SD).

	n	TTE (s)	W_{peak} (W)	W_{peak} ($W \cdot kg^{-1}$)	VO_{2peak} ($L \cdot min^{-1}$)	VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)
Men	7	502 ± 80	187.3 ± 26.7	2.42 ± 0.15	4.60 ± 0.41	59.8 ± 4.9
Women	3	399 ± 90	114.8 ± 22.6	1.97 ± 0.27	2.57 ± 0.48	44.2 ± 5.4

TTE = time to exhaustion for incremental test; W_{peak} = peak power output from incremental test; VO_{2peak} = peak oxygen uptake from incremental test.

Tables 4 and 5 show Pearson correlation coefficients for all laboratory measures with RS. Absolute VO_{2peak} and W_{10} were significantly correlated to RS (r = 1.00) for women. None of the measures correlated significantly to RS for men. Due to the small number of subjects completing both laboratory testing and the race, further analysis of these data was considered inappropriate.

Table 4. Correlation coefficients with 95% confidence intervals in parentheses for 10- and 60-second tests of upper body power to NorAm race speed†.

	n	W_{10} (W)	W_{10} (W·kg^{-1})	W_{60} (W)	W_{60} (W·kg^{-1})
Men	7	.40	.42	.14	.11
		(-.51 - .89)	(-.49 - .89)	(-.69 – .81)	(-.70 - .80)
Women	3	1.00*	.96	.99	.93

† Confidence intervals could not be calculated for women due to low subject number.
* Denotes significant correlation ($P < .05$).
W_{10} = power output from 10-second test; W_{60} = power output from 60-second test.

Table 5. Correlation coefficients with 95% confidence intervals in parentheses for peak power output and oxygen uptake measures to NorAm race speed†.

	n	W_{peak} (W)	W_{peak} (W·kg^{-1})	VO_{2peak} (L·min^{-1})	VO_{2peak} (ml·kg^{-1}·min^{-1})
Men	7	.06	-.05	.60	.52
		(-.73 - .78)	(-.77 - .73)	(-.28 - .93)	(-.38 - .92)
Women	3	.99	.96	1.00*	.99

† Confidence intervals could not be calculated for women due to low subject number.
* Denotes significant correlation ($P < .05$).
W_{peak} = peak power output from incremental test; VO_{2peak} = peak oxygen uptake from incremental test.

Nineteen subjects (13 men, 6 women) volunteered to participate in laboratory testing and compete in the Spam Cup race. Eleven of these subjects (8 men, 3 women) were also participants in the NorAm part of the study and were not re-tested. All 19 subjects completed the laboratory testing, but only 15 (10 men, 5 women) were able to compete in the race. The remaining 4 subjects (3 men, 1 woman) did not race due to injury or illness. Age, height, weight, and % body fat of the 15 racers are summarized in Table 6.

Table 6. Spam Cup subject characteristics (Mean ± SD).

	n	Age (years)	Height (cm)	Weight (kg)	% Body Fat
Men	10	23.5 ± 7.9	181.7 ± 7.1	73.9 ± 7.6	10.6 ± 2.5
Women	5	25.6 ± 6.3	162.1 ± 2.8	58.2 ± 4.6	17.7 ± 3.2
All	15	24.2 ± 7.3	175.2 ± 11.2	68.7 ± 10.1	13.6 ± 4.5

Mean RS during the Spam Cup race was 4.82 ± 0.63 $m \cdot s^{-1}$ for all subjects, 4.23 ± 0.36 $m \cdot s^{-1}$ for women, and 5.12 ± 0.51 $m \cdot s^{-1}$ for men. Tables 7 and 8 summarize the laboratory test results. All measures are presented as both absolute and relative to body mass.

Table 7. Results of 10- and 60-second tests of upper body power – Spam Cup subjects (Mean ± SD).

	n	W_{10} (W)	W_{10} ($W \cdot kg^{-1}$)	W_{60} (W)	W_{60} ($W \cdot kg^{-1}$)
Men	10	248.3 ± 51.9	3.34 ± 0.47	190.0 ± 37.7	2.56 ± 0.32
Women	5	129.4 ± 16.8	2.23 ± 0.26	101.0 ± 17.2	1.74 ± 0.29
All	15	208.7 ± 71.9	2.96 ± 0.68	160.3 ± 54.0	2.28 ± 0.50

W_{10} = power output from 10-second test; W_{60} = power output from 60-second test.

Table 8. Results of incremental test to exhaustion – Spam Cup subjects (Mean ± SD).

	n	TTE (s)	W_{peak} (W)	W_{peak} ($W \cdot kg^{-1}$)	VO_{2peak} ($L \cdot min^{-1}$)	VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)
Men	10	457 ± 83	170.2 ± 29.4	2.29 ± 0.21	4.24 ± 0.49	57.4 ± 4.1
Women	5	300 ± 42	90.0 ± 10.6	1.55 ± 0.20	2.51 ± 0.31	43.2 ± 4.7
All	15	404 ± 104	143.4 ± 46.0	2.05 ± 0.41	3.66 ± 0.94	52.7 ± 8.0

TTE = time to exhaustion for incremental test; W_{peak} = peak power output from incremental test; VO_{2peak} = peak oxygen uptake from incremental test.

Tables 9 and 10 show Pearson correlation coefficients for all measures with RS. When the data for male and female subjects were analyzed together, all measures were significantly related to RS (r = .67-.90). Peak power output demonstrated the highest correlation to RS, whether expressed as an absolute (r = .87) or relative value (r = .90). When results were analyzed separately by gender, only W_{peak} (both absolute and relative) and VO_{2peak} were significantly related to RS for men, with relative W_{peak} demonstrating the highest correlation (r = .81). Relative measures of W_{10}, W_{60}, and W_{peak} all showed significant correlations with RS (r ≥ .93) for women. Scatterplots of laboratory measures versus race speed (including least-squares regression equations) are shown in Figures 2-9 (Appendix B).

Table 9. Correlation coefficients with 95% confidence intervals in parentheses for 10- and 60-second tests of upper body power to Spam Cup race speed.

	n	W_{10} (W)	W_{10} ($W \cdot kg^{-1}$)	W_{60} (W)	W_{60} ($W \cdot kg^{-1}$)
Men	10	.61	.53	.60	.52
		(-.03-.90)	(-.15-.87)	(-.05-.89)	(-.16-.87)
Women	5	.60	.96*	.71	.94*
		(-.60-.97)	(.51-.99)	(-.46-.98)	(.34-.99)
All	15	0.81*	.81*	.82*	.82*
		(.51-.94)	(.51-.94)	(.53-.94)	(.53-.94)

* Denotes significant correlation ($P < .05$).
W_{10} = power output from 10-second test; W_{60} = power output from 60-second test.

Table 10. Correlation coefficients with 95% confidence intervals in parentheses for peak power output and oxygen uptake measures to Spam Cup race speed.

	n	W_{peak} (W)	W_{peak} ($W \cdot kg^{-1}$)	VO_{2peak} ($L \cdot min^{-1}$)	VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)
Men	10	.75*	.81*	.67*	.37
		(.23-.94)	(.37-.95)	(.07-.91)	(-.34-.81)
Women	5	.73	.93*	-.44	-.25
		(-.43-.98)	(.26-.99)	(-.95-.73)	(-.93-.81)
All	15	.87*	.90*	.78*	.67*
		(.64-.96)	(.72-.97)	(.45-.93)	(.24-.88)

* Denotes significant correlation ($P < .05$).
W_{peak} = peak power output from incremental test; VO_{2peak} = peak oxygen uptake from incremental test.

Two male subjects had performed little or no ski-specific training prior to the race. One subject had missed 2 months of fall training due to illness, and had resumed normal training approximately 2 weeks before the race. The other had completed a great deal of cycling, running, and general strength training in the months prior to the race, but had done no roller skiing or snow skiing since the previous winter. Given these factors, it was considered appropriate to re-analyze the data with these subjects excluded. Tables 11 and 12 show correlation coefficients with RS with these subjects excluded. When data for all subjects were analyzed together, correlations for all measures increased (r = .73-.95). When data for men were analyzed separately, all measures showed significant correlations except relative W_{10}, W_{60}, and VO_{2peak}. Scatterplots of laboratory measures versus race speed (including least-squares regression equations) are shown in Figures 10-17 (Appendix B). The aforementioned male subjects have been removed from the data set in these figures.

Table 11. Correlation coefficients with 95% confidence intervals in parentheses for 10- and 60-second tests of upper body power to Spam Cup race speed (two male subjects excluded).

	n	W_{10} (W)	W_{10} ($W \cdot kg^{-1}$)	W_{60} (W)	W_{60} ($W \cdot kg^{-1}$)
Men	8	.90*	.67	.84*	.60
		(.53-.98)	(-.07-.93)	(.33-.97)	(-.19-.92)
Women	5	.60	.96*	.71	.94*
		(-.60-.97)	(.51-.99)	(-.46-.98)	(.34-.99)
All	13	.93*	.91*	.92*	.91*
		(.78-.98)	(.72-.97)	(.75-.98)	(.72-.97)

* Denotes significant correlation ($P < .05$).
W_{10} = power output from 10-second test; W_{60} = power output from 60-second test.

Table 12. Correlation coefficients with 95% confidence intervals in parentheses for peak power output and oxygen uptake measures to Spam Cup race speed (two male subjects excluded).

	n	W_{peak} (W)	W_{peak} ($W \cdot kg^{-1}$)	VO_{2peak} ($L \cdot min^{-1}$)	VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)
Men	8	.89*	.72*	.85*	.06
		(.49-.98)	(.03-.95)	(.36-.97)	(-.68-.74)
Women	5	.73	.93*	-.44	-.25
		(-.43-.98)	(.26-.99)	(-.95-.73)	(-.93-.81)
All	13	.94*	.95*	.88*	.73*
		(.81-.98)	(.84-.98)	(.64-.96)	(.30-.91)

W_{peak} = peak power output from incremental test; VO_{2peak} = peak oxygen uptake from incremental test.

CHAPTER FIVE

DISCUSSION

Numerous studies have confirmed the importance of upper body power (UBP) in cross-country ski racing, using UBP measures varying from 5 seconds to several minutes (Gaskill et al., 1999; Heil et al., 2004; Mahood et al., 2001; Rundell, 1995; Rundell & Bacharach, 1995; Staib et al., 2000). Only Staib et al. (2000) have attempted to differentiate between short and long term UBP and identify the contributions of both to race performance. However, their test for short term UBP lasted a minimum of 100 seconds. Prior to the present study, UBP measures of shorter duration than this have never been compared to long term measures as predictors of race performance.

The present study was also the first to correlate UBP to performance in a single classical race. Previous studies have used skating races or a combination of both skating and classical races as performance measures. The distinction between classical and skating races as a performance measure is important due to the different UBP demands of the two styles. The upper body has been shown to contribute 50% or more of the force required for forward propulsion in uphill skating (Street, 1989), but only 15-30% in uphill classical skiing (Komi, 1987). Conversely, the upper body may provide 100% of the necessary force during classical skiing in flat and gently rolling terrain due to the use of the double pole technique, which involves arms only. During skating on similar terrain, the upper body is heavily used, but the legs continue to contribute significantly to forward movement as well (Millet, Hoffman, Candau, & Clifford, 1998). Thus, studies evaluating the importance of UBP in skating or a combination of both styles may not accurately represent the role of UBP in classical performance alone.

Correlations of Upper Body Power Measures with Race Speed

This study used three different tests, performed on a double poling ergometer, to evaluate UBP: average power output in a 10-second test (W_{10}), average power output in a 60-second test (W_{60}), and peak power output achieved in an incremental test to exhaustion lasting 240-630 seconds (W_{peak}). Peak oxygen uptake (VO_{2peak}) was also measured during the incremental test. Laboratory results were compared to average race speed (RS) achieved during one of two classical style races: the West Yellowstone NorAm race (6-km for women, 12-km for men), or the West Yellowstone Spam Cup (10-km for all skiers). Correlation coefficients found between UBP measures and RS for the NorAm group varied widely (Tables 4 and 5), and were considered inappropriate for further analysis due to a low number of subjects completing the race. In the Spam Cup group, all measures of UBP and VO_{2peak} were found to correlate significantly with RS, both as absolute values and when expressed relative to body mass (Tables 9 and 10).

Correlations between UBP measures and performance decreased when data were analyzed separately for men and women, a similar trend as that observed by Gaskill et al. (1998). Only relative measures of W_{10}, W_{60}, and W_{peak} showed significant relationships with RS for women, all with correlations of .93 or greater. Relative and absolute VO_{2peak} for women showed non-significant negative correlations with race speed. Given the small number of female subjects completing the race (n = 5), these results may have been skewed by the fact that the race winner had scores below the mean for all absolute measures. It should also be noted that correlations for absolute measures were all above .60, and may have achieved significance with a larger number of subjects. Among men (n = 10), only W_{peak} (both absolute and relative) and absolute VO_{2peak} correlated significantly to RS. Both absolute (r = .75) and relative W_{peak} (r = .81) showed higher correlations than absolute VO_{2peak} (r = .67).

Exclusion of two male outliers from the analyses increased correlations for all measures (Tables 11 and 12). When the men's data were analyzed separately without the outliers, significant correlations were found for all measures except relative measures of W_{10}, W_{60} and VO_{2peak}. Absolute W_{10} and W_{peak} showed the highest correlations (r = .90 and .89, respectively). In an analysis of all subjects with outliers excluded, correlations were all between .91 and .95, except absolute and relative VO_{2peak} (r = .88 and .73, respectively). All subsequent discussion will refer to correlations found with the outliers excluded.

Short vs. Long Term Measures of Upper Body Power

These findings appear to indicate that both short and long term UBP contribute to determining classical race performance. The high correlations between RS and long term UBP (as measured by W_{peak} in this study) were not surprising, considering that the race lasted 29-44 minutes. However, the equally high correlations between RS and two short term measures (W_{10} and W_{60}) were less expected, given the traditional view of cross-country ski racing as an aerobic endurance sport.

A possible explanation for these findings is the fact that the variation in terrain of a cross-country ski race allows competitors frequent rest periods. Measurement of oxygen uptake and blood lactate values during a simulated 14-km race indicates that both elite and sub-elite competitors ski at near-maximal intensity on uphills and use ensuing downhills to recover (Mygind, Andersen, & Rasmussen, 1994). Thus, the ability to generate power anaerobically during a cross-country ski competition may be of greater importance than in other endurance events. However, since the upper body plays a smaller role during uphill classical skiing (Komi, 1987), the work-recovery patterns of cross-country ski racing are probably not the only explanation for the high predictive value of short term UBP measures.

It should also be noted that both W_{10} and W_{60} correlated highly with W_{peak} (r = .96 and .97, respectively, for absolute measures, and r = .91 and .94, respectively, for relative measures) for the entire group of subjects (both NorAm and Spam Cup). This supports earlier suggestions that a short term test of power output may be a predictor of sustainable long term power output, or long term UBP (Heil et al., 2004; Nilsson et al., 2004). Given the high correlations between W_{10}, W_{60}, and W_{peak}, and of all measures with RS, both long and short term tests of UBP may be measuring similar characteristics in an athlete. Recent studies on maximal strength training have suggested that increases in the rate of force production during double poling may result in improved economy and an increase in time to exhaustion while double poling on an ergometer (Hoff et al., 2002; Hoff et al., 1999; Osteras et al. 2002). An increase in maximal force output was also suggested as a possible mechanism for the observed improvement in economy, due to a lower relative intensity of exercise. Since the W_{10} test in the present study required maximal power output over a short period of time, it seems likely that both maximal force output and rate of force production determined the results of this test. Therefore, a high W_{10} may be associated with a high double poling economy, which would certainly improve performance in a race of any length. A high W_{peak} or W_{60} may be largely due to the high double poling economy suggested by the W_{10} test; hence the high correlation of these three measures with each other, and of all three measures with RS. Future studies comparing short and long term measures of UBP to race performance might include measures of double poling economy and rate of force production, to determine whether both short and long term measures of UBP are in fact affected by these factors.

Measures of Power Output vs. Measures of Oxygen Uptake

Although absolute and relative VO_{2peak} were significantly related to classical race performance for all subjects ($r = .88$ and $.73$, respectively), both absolute and relative W_{peak} showed stronger relationships with RS ($r = .94$ and $.95$, respectively). Correlations for W_{peak} determined separately for both genders were also higher than each gender's respective VO_{2peak} correlations. Most other studies on UBP in cross-country skiing have shown similar results, regardless of whether peak power output was directly measured or estimated with a criterion measure (Gaskill et al., 1999; Heil et al., 2004; Mahood et al., 2001; Rundell, 1995; Rundell & Bacharach, 1995). Staib et al. (2000) found double poling VO_{2peak} to be a better predictor of performance than peak power output during a relatively short (100-322 seconds) incremental test to exhaustion ($r = -.74$ and $-.68$, respectively); however, time to exhaustion in the VO_{2peak} test (a criterion measure for peak power output) showed an even higher correlation ($r = -.80$) than VO_{2peak} itself. Other studies have found power measures to be good predictors of performance for swimming (Hawley, Williams, Vickovic, & Handcock, 1992), running (Noakes, Myburgh, & Schall, 1990), rowing (Bourdin, Messonnier, Hager, & Lacour, 2004), and cycling (Coyle et al., 1991; Hawley & Noakes, 1992; Heil, Murphy, Mattingly, & Higginson, 2001). Several of these studies have directly compared power output measures to measures of oxygen uptake, and have found power output to correlate more closely with performance (Bourdin et al., 2004; Coyle et al., 1991; Heil et al., 2001; Noakes et al., 1990).

A logical explanation for the high predictive value of these various peak power measures is that a single measure of peak power output accounts for VO_{2peak}, VO_2 at lactate threshold (LT), and movement economy. These three physiological variables are considered to be the three main determinants of endurance performance (Pate & Branch, 1992). In a laboratory test of peak power output, an athlete with a high VO_{2peak} may not be able to achieve a high peak power output due to poor movement economy or an inability to work at a high percentage of VO_{2peak} without significant lactate accumulation. Similarly, an athlete with a low VO_{2peak} may be able to achieve a high peak power output through good movement economy and a high VO_2 at LT. In either case, all three variables will influence an athlete's score for a peak power measure. Thus, peak power measures have higher predictive value than VO_{2peak} alone. A high VO_{2peak} is still a crucial element of endurance performance, but VO_{2peak} alone does not guarantee competitive success, as this and many other studies have shown.

Relative vs. Absolute Measures of Power Output

Cycling studies have shown that both absolute and relative measures of power output can be accurate predictors of performance, depending on what type of terrain is chosen for the performance measures. Coyle et al. (1991) and Hawley and Noakes (1992) found absolute power output to correlate more highly with performance in a flat time trial, while Heil et al. (2001) found that relative measures of power output were better predictors of uphill time trial performance. As Heil et al. (2001) observed, the primary external resistance in an uphill time trial is gravitational. Gravitational resistance increases proportionally with body mass. Thus, peak power output expressed relative to body mass correlates highly with uphill time trial performance. Conversely, the primary external resistance to flat cycling is aerodynamic. Aerodynamic resistance is proportional to a cyclist's frontal area, which does not increase proportionally with body mass (Heil, 2001; Heil, 2002). Thus, body mass plays a much smaller role in determining external resistance in flat cycling, as reflected by the high correlation of absolute peak power output with flat time trial performance.

The effects of body mass on cross-country skiing performance are more difficult to evaluate because race courses include a wide variety of terrain, and thus a wide variety of external resistances. Bergh (1987) used dimensional analysis to compare a skier's power supply to the power demand imposed by external resistance during classical skiing. His model assumed that aerobic power increased proportionally to body mass (m_b) raised to the 0.67 power (anaerobic power production was disregarded). Bergh found that power demand for most sources of resistance increased proportionally to $m_b^{0.67}$ during skiing on flat and gently rolling terrain. The two exceptions were frictional forces (P_μ) and power required to increase potential energy during the stride (P_p). According to Bergh's model, P_μ was greater than P_p on flats and slight uphills, and was the major determinant of the influence of m_b. Since P_μ was found to increase proportionally to

$m_b^{0.33}$ while aerobic power supply increased proportionally to $m_b^{0.67}$, larger skiers' greater power output outweighed the increased resistance they faced on flat and slightly uphill terrain. Gravitational force was assumed to be the primary resistance on uphills. Since gravitational forces increase in direct proportion to body mass, smaller skiers were favored on uphills. Conversely, gravitational force provided power for downhill skiing, and was resisted by aerodynamic and frictional forces. Neither of the resistive forces was found to increase proportionally to body mass, giving larger skiers an advantage on downhills.

In the present study, no attempt was made to calculate the degree to which power output increased with increased body mass. However, skiers with larger body mass did tend to have higher absolute power output for all measures of UBP ($r \geq .90$). According to Bergh's analysis (1987), the larger, more powerful skiers may have had an advantage on flat and gently rolling terrain. As discussed previously, the double pole technique is used in this terrain, during which the upper body provides virtually all of the power for forward movement. Therefore, skiers with high absolute UBP should be favored on a flat section of a cross-country ski course in spite of the likelihood that these skiers also have a higher body mass.

Relative UBP would seem less likely to be a good predictor of classical race performance. Although body mass is a major factor in uphill skiing, skiers use relatively little UBP during uphill classical skiing (Komi, 1987), instead overcoming resistance with power generated by both upper and lower body. If skiing were a sport that used only the upper body, as cycling uses only the lower body, higher correlations of relative UBP with uphill skiing performance would be expected, similar to the high correlations found by Heil et al. (2001) between relative peak power output and uphill cycling performance.

However, the theoretical advantage of absolute over relative UBP measures in predicting race performance has not been clearly established in previous research. Although Rundell (1995) and Staib et al. (2000) did find absolute UBP to correlate more closely with performance than relative UBP, Gaskill et al. (1999) and Heil et al. (2004) found relative UBP to be a slightly better predictor of performance, while Rundell and Bacharach (1995) found little difference between the two. The present study showed similarly mixed results: absolute UBP measures showed higher correlations for men but lower correlations for women, and were similar for the entire group. Based on dimensional analysis (Bergh, 1987), it seems logical to speculate that subjects with the highest absolute UBP values did gain an advantage on the flat and gently rolling areas of the course, where the double pole technique predominated. However, many of these skiers also had higher body mass, and may have been unable to maintain a high speed on the uphills, thus resulting in a lower average race speed. It is likely that the fastest skiers were those who had enough absolute UBP to maintain high speed on flat terrain, but also had the ability to generate enough whole body power relative to body mass to ski fast on the uphills. In summary, the variation in terrain may have obscured the relationship between absolute UBP and speed on flat terrain, and correlations between absolute UBP measures were no greater than those of relative measures. A repeat of the present study using an entirely uphill or entirely flat course as a performance measure might help to better identify the role of absolute versus relative UBP in various sections of a classical race course.

Relative vs. Absolute Measures of Oxygen Uptake

Among all subjects, absolute VO_{2peak} correlated more highly with RS than relative VO_{2peak} ($r = .88$ and .73, respectively). Neither absolute nor relative VO_{2peak} were significantly correlated with RS for women. For men, only absolute VO_{2peak} showed a significant correlation with RS ($r = .85$). This agrees with previous research by Staib et al. (2000), who found a high correlation between race points and absolute, but not relative, upper body VO_{2peak} for adult males.

These findings seem to contradict Mahood et al. (2001), who found a high correlation ($r = -.74$) between relative upper body VO_{2peak} and 10-km skate rollerski time (no data for absolute VO_{2peak} was reported). A possible explanation for this finding is that the both the present study and Staib et al. (2000) used classical races to define all or part of the performance variable, while Mahood et al. used a skating time trial. Upper body power is particularly important during uphill skating (Street, 1989). Since the primary source of resistance on an uphill is gravitational and increases proportionally to body mass, adjusting a measure of power supply (in this case upper body VO_{2peak}) to account for body mass would likely give a more accurate idea of a skier's ability to overcome resistance during uphill skating. The terrain used by Mahood et al. for the 10-km time trial was not described. However, the course must have included several uphill sections where relative upper body VO_{2peak} became a major determinant of performance.

Conversely, the upper body plays a much smaller role in uphill classical skiing (Komi, 1987). Instead, UBP is mainly used on flat terrain, where body mass affects external resistance to a lesser degree than on uphills (Bergh, 1987). Thus, an absolute measure of power supply (again, upper body VO_{2peak} in this case), would likely be a better predictor of performance for classical skiing, as shown by the results of Staib et al. (2000) and the present study.

Prediction of Race Performance

All UBP measures correlated significantly with RS when data for all subjects were analyzed together. Thus, any of these measures would seem to be useful in predicting performance. A simulation using the least-squares derived equations for predicting RS from the various UBP measures could give an estimate of performance changes with changes in a given UBP measure. For example, the equation for predicting RS from absolute W_{10} is given by Figure 10 ($r = .93$, SEE = $\pm$ 0.25 $m \cdot s^{-1}$):

$$RS = 3.27 + 0.008 \times W_{10} \quad (2)$$

Mean W_{10} for all subjects was 202.5 W. Table 13 shows predicted RS and race time for a 10-km classical race based on a 5% increase or decrease in W_{10}.

Table 13. Estimated changes in race speed (RS) and time for 10-km classical race with a 5% increase or decrease in mean W_{10} (202.5 W). RS based on least-squares regression of 10-km classical race times and average power output for a 10-second test (W_{10}). $RS = 3.27 + 0.008 \times W_{10}$; $r = .93$, SEE = $\pm$ 0.25 $m \cdot s^{-1}$.

	W_{10} (W)	Race Speed ($m \cdot s^{-1}$)	Race Time (min:sec)
Mean W_{10} (-5%)	192.4	4.81	34:39
Mean W_{10}	202.5	4.89	34:05
Mean W_{10} (+5%)	212.6	4.97	33:32

If the simulation is repeated using absolute W_{60} as the independent variable, the equation for predicting RS from absolute W_{60} is given by Figure 12 (r = .92, SEE = ± 0.25 m·s^{-1}):

$$RS = 3.24 + 0.011 \times W_{60} \quad (3)$$

Mean W_{60} for all subjects was 156.2 W. Table 14 shows predicted RS and race time for a 10-km classical race based on a 5% increase or decrease in W_{60}.

Table 14. Estimated changes in race speed (RS) and time for 10-km classical race with a 5% increase or decrease in mean W_{60} (156.2 W). RS based on least-squares regression of 10-km classical race times and average power output for a 60-second test (W_{60}). RS = 3.24 + 0.011 x W_{60}; r = .92, SEE = ± 0.25 m·s^{-1}.

	W_{60} (W)	Race Speed (m·s^{-1})	Race Time (min:sec)
Mean W_{60} (-5%)	148.4	4.87	34:13
Mean W_{60}	156.2	4.96	33:36
Mean W_{60} (+5%)	164.0	5.04	33:04

Lastly, if the simulation is repeated using absolute W_{peak} as the independent variable, the equation for predicting RS from absolute W_{peak} is given by Figure 14 (r = .94, SEE = ± 0.22 m·s^{-1}):

$$RS = 3.15 + 0.012 \times W_{peak} \quad (4)$$

Mean W_{peak} for all subjects was 145.6 W. Table 15 shows predicted RS and race time for a 10-km classical race based on a 5% increase or decrease in W_{peak}.

Table 15. Estimated changes in race speed (RS) and time for 10-km classical race with a 5% increase or decrease in mean W_{peak} (141.3 W). RS based on least-squares regression of 10-km classical race times and peak power output in an incremental test to exhaustion (W_{peak}). RS = 3.15 + 0.012 x W_{peak}; r = .94, SEE = ± 0.22 $m \cdot s^{-1}$.

	W_{peak} (W)	Race Speed ($m \cdot s^{-1}$)	Race Time (min:sec)
Mean W_{peak} (-5%)	134.2	4.76	35:01
Mean W_{peak}	141.3	4.85	34:22
Mean W_{peak} (+5%)	148.4	4.93	33:49

Depending on which UBP measure is used in the simulation, a 5% change in power output changes estimated race time by as much as 39 seconds, which is a major time difference in a 10-km event. The difference between first and second place in the women's race was 28 seconds, while the men's race was decided by less than 10 seconds. Further, this race was a small local event, with relatively few participants (15 women, 30 men); larger races are generally more closely contested. For example, in the men's 10-km classical race at the 2005 U.S. National Championships, the silver medalist and 10th place finisher were separated by 35 seconds.

It should be noted that the subjects in this study were very heterogeneous with regard to age, gender, and skill level. Skiers ranged from elite collegiate skiers to well-trained recreational racers, with ages from 18-42 years. As data from Gaskill et al. (1998) indicates, the predictive value of UBP measures decrease when groups are sorted according to age, gender, and skill level. Thus, it is likely that small changes in UBP would not yield such large changes in performance among a more homogeneous group of skiers, such as the competitors in the aforementioned National Championship race. Still, even if the gains from an increase in UBP were only a fraction of what this simulation predicts, the improvement in any skier's time and place would still be quite significant in a well-attended, closely contested race. Future research should focus on evaluating the relationship of UBP to classical race performance in various homogeneous groups of skiers, as Gaskill et al. have done for skating performance.

CHAPTER SIX

CONCLUSIONS

The findings of this study indicate that both long and short term upper body power (UBP) were good predictors of performance in a 10-km classical race among a heterogeneous group of skiers. Long term UBP was evaluated by measuring peak power output achieved in an incremental test to exhaustion lasting 240-630 seconds (W_{peak}). Short term UBP was evaluated by measuring average 10-second power output (W_{10}) and average 60-second power output (W_{60}). Further, UBP measures were superior to measures of peak oxygen uptake (VO_{2peak}) for predicting classical race performance. Although correlations decreased when data were analyzed separately by gender, the strong predictive value of UBP measures remained apparent. Lastly, both W_{10} and W_{60} correlated highly with W_{peak}.

These findings have several practical implications. First, testing of VO_{2peak} does not appear to be necessary to predict race performance, since W_{peak} proved to be a better predictor of race performance than VO_{2peak}. A test associated with peak power output, such as the double pole time trial used by Mahood et al. (2000), would be a viable option for most skiers. Although most skiers do not have access to an upper body ergometer, such devices are becoming more common, and could be widely available to coaches and athletes in the near future. Either option would probably be more convenient than VO_{2peak} testing.

Testing for both long and short term UBP also appears to be unnecessary, as these measures are closely related and may be measuring the same characteristics. Coaches might find a short term UBP test easier and more convenient to administer. Further, a shorter test would likely be less disruptive to an athlete's planned training, whereas a long test might require a few days' recovery.

With regard to training, these findings support the notion that training to improve short term UBP may also improve endurance performance. Given the high correlations of both long and short term UBP with RS, a variety of training methods may be necessary to fully develop the UBP needed for performance. Nilsson et al. (2004) have found long (180-second) and short (20-second) double poling intervals to be effective at developing long and short term UBP, respectively. Since research comparing the performance effects of long and short term UBP training is lacking, a balance of long and short term training might be the most pragmatic approach until this question is investigated further.

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APPENDICES

APPENDIX A

SUBJECT CONSENT FORM

SUBJECT CONSENT FORM FOR PARTICIPATION IN HUMAN RESEARCH
MONTANA STATE UNIVERSITY – BOZEMAN

PROJECT TITLE: Role of upper body power in classical cross-country skiing performance.

FUNDING: This study is not a funded project.

PROJECT DIRECTOR: Nathan Alsobrook
Department of Health and Human Development
Hoseaus Complex, Montana State University
Bozeman, MT 59715, (406) 209-0881, nalsobrook@montana.edu

PURPOSE: The purpose of this project is to assess the relationship between upper body power and classical cross-country ski racing performance. To be eligible for participation in this study, participants must intend to compete in either the NorAm classical race on November 26, 2004 or the Spam Cup race on December 11, 2004 (both races will be held in West Yellowstone, MT). Results of these races will be correlated to results of the upper body power tests described below to evaluate the role of upper body power in determining classical ski racing performance.

Each participant is presented with this *Informed Consent Document* which explains the purpose of the testing, as well as expected risks and benefits associated with participation. Participants will be screened by the project director using responses provided by participants in a Health History Questionnaire. If this screening raises questions as to the participant's ability to safely complete the testing, the participant will need to obtain written medical clearance from his/her physician prior to lab testing. This procedure is in accordance with policies formulated by the American College of Sports Medicine.

PROJECT OUTLINE: If you agree to participate, you will be required to make three visits to the Movement Science Laboratory (basement of Romney Building) at Montana State University (Bozeman). Each visit will last approximately one hour and will be scheduled 24-48 hours AFTER your last "hard" workout. It is important that you refrain from ingesting any medications, including caffeine or aspirin, for at least 2 hours before each visit. If any medications were taken (such as cold or allergy medicine), please inform the lab personnel PRIOR to testing – we will gladly reschedule your visit. If you use an inhaler to treat asthma, make certain to bring the inhaler with you to the lab. You should arrive at the lab ready to engage in high intensity exercise. Therefore, participants should dress (ie. running shoes, shorts, short sleeve shirt or tank top, etc.), eat, and drink fluids appropriately. During the first visit, participants should also bring a close fitting swimsuit for hydrostatic weighing (described below).

The first lab visit will take place 10-21 days before the NorAm or Spam Cup classical ski race. Your age, height, and weight will be recorded. **Body composition** will then be tested using hydrostatic weighing (underwater weighing). Body composition is a measure of your percent body fat. You will need to change into a swimsuit (private changing facilities will be available), and sit on a chair-like device in a tank full of water. You will be asked to exhale as much air as possible before submerging your head underwater for 10-15 seconds. This procedure will be repeated 6 times. After hydrostatic weighing, you will change into your workout clothes and spend 15 minutes familiarizing yourself with the double-poling ergometer used for all upper body power testing in this study. This ergometer is a converted rowing machine, with ski poles attached to a sliding platform. Pushing on the poles causes this platform to slide backward and pull on a chain, which turns a flywheel to create resistance. The net effect is a stationary activity that effectively simulates the double-poling motion of the upper body. The 15-minute familiarization session will include two high-intensity work periods identical to the 30-second and 60-second tests described below.

The second lab visit will take place two to three days after the familiarization session. You will warm up for 5 minutes before performing 3 consecutive 30-second trials on the double-poling ergometer. This test is designed to measure your **maximal instantaneous upper body power**. During each trial, you will gradually build momentum for the first 20 seconds before finishing with an all-out effort for the last 10 seconds. The effort is similar to sprinting 100 meters as fast as possible. Each trial will be followed by 3 minutes of rest. The final 30-second trial will be followed by 5 minutes of rest. You will then perform a single 60-second double-poling test, designed to measure your **maximal anaerobic upper body power**. The effort required for this test is similar to a 400 meter dash.

The third lab visit will take place two to three days after the second visit, and a minimum of three days before the NorAm or Spam Cup race. You will warm up for 5 minutes before performing an incremental test to exhaustion on the double-poling ergometer. This test is designed to measure your **aerobic upper body power**. This test determines your body's ability to uptake, transport, and utilize oxygen (VO_{2peak}) in the working muscles during double-poling. The test will start out at an easy intensity (low power output in Watts), similar to slow double poling across flat terrain, and increase in difficulty every 1-2 minutes. *The goal of this test is to last as long as possible before you reach the point where you cannot maintain the required workload.* The effort at the highest intensity of this test is similar to running an 800-meter race. During this test, you will be breathing through a mouthpiece (like a snorkel mouthpiece) so that the amount of oxygen you are using can be measured. At the same time, you will be wearing a *heart rate monitor* to measure heart rate via telemetry. You may also be asked to provide a rating of your perceived exertion (RPE) on a scale of 0 to 10 (resting to maximal intensity exercise) during the test.

<u>POTENTIAL RISKS</u>: You should be aware that the three double-poling tests may cause extreme fatigue immediately after the tests and possibly during the next day. VO_{2peak} testing (the test to exhaustion) also involves a chance of precipitating a cardiac event (such as abnormal heart rhythms) or even death. However, the possibility of such an

occurrence is very slight (less than 1 in 10,000) since 1) you are in good physical condition with no known symptoms of heart disease, and 2) the test will be administered by trained personnel (American Red Cross CPR certified and aware of the lab's emergency action plan). *These risks should not exceed those experienced by trained athletes in actual race competition.* The measuring devices (heart rate monitor and mouthpiece) may feel somewhat restrictive and/or uncomfortable during testing, but all possible adjustments will be used to achieve the greatest comfort for you. The hydrostatic weighing may also involve some discomfort, due to the necessity of remaining underwater for several seconds at a time. All possible precautions will be taken to ensure your safety and make you feel comfortable before any testing takes place.

<u>BENEFITS</u>: Each participant will receive specific information about their own test results. In addition, you will be told the average test values achieved by the group of participants, to help you interpret your results relative to other well-trained skiers.

<u>CONFIDENTIALITY</u>: The data and personal information obtained from this project will be regarded as privileged and confidential. Other than the project director and assisting investigators, only you will know your personal results. Your test results will not be released to anyone except upon your written request/consent. Your right to privacy will be maintained in any ensuing analysis and/or presentation of the data by using coded identifications of each person's data.

<u>FREEDOM OF CONSENT</u>: At any time you may withdraw consent for participation in writing, by telephone, or in person without prejudice or loss of benefits (as described above). *Participation in this project is completely voluntary.*

In the UNLIKELY event that your participation in this research results in physical injury to you, the project director will advise and assist the participant in receiving medical treatment. Montana State University cannot be held responsible for injury, accidents, or expenses that may occur as a result of traveling to and from your appointments at the Movement Science Laboratory OR to and from the NorAm or Spam Cup races. No compensation for injury will be provided. Further information regarding medical treatment may be obtained by calling the project director, Nathan Alsobrook, at (406) 209-0881. You are encouraged to express any questions, doubts, or concerns regarding this project. The project director will attempt to answer all questions to the best of his ability prior to any testing. The project director fully intends to conduct the study with your best interest, safety, and comfort in mind. *Additional questions about the rights of human subjects can be answered by the Chairman of the Montana State University Human Subjects Committee, Mark Quinn, at (406) 994-5721.*

<<< KEEP THIS PAGE FOR YOUR OWN RECORDS >>>

<u>PROJECT TITLE</u>: Role of upper body power in classical cross-country skiing performance

<u>STATEMENT OF AUTHORIZATION</u>

I, *the participant*, have read the Informed Consent Document and understood the discomforts, inconvenience, risks, and benefits of this project. I, ______________________________ (print your name), agree to participate in the project described in the preceding pages. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Signed:_________________________________ Age:________ Date:_______________
Subject's Signature

If you, the participant, are **<u>less than 18 years of age</u>** at the time of signing this consent form, you MUST have the consent of a parent or legal guardian as indicated by their signature below.

I, *the parent or legal guardian*, have read the Informed Consent Document and understand the discomforts, inconvenience, and risk of this study. I, ______________________________ (printed name of parent or guardian), related to the participant as ______________________ (state relationship to the skier), agree to the participation of ______________________________ (print the name of the participant) in the project described in the preceding pages. I understand that I may later refuse participation in this project and that the participant, through his/her own action or mine, may withdraw from the study at any time.

Signed:___________________________________ Date:_______________
Parent or Legal Guardian

APPENDIX B

SCATTERPLOTS OF LABORATORY MEASURES VS. RACE SPEED

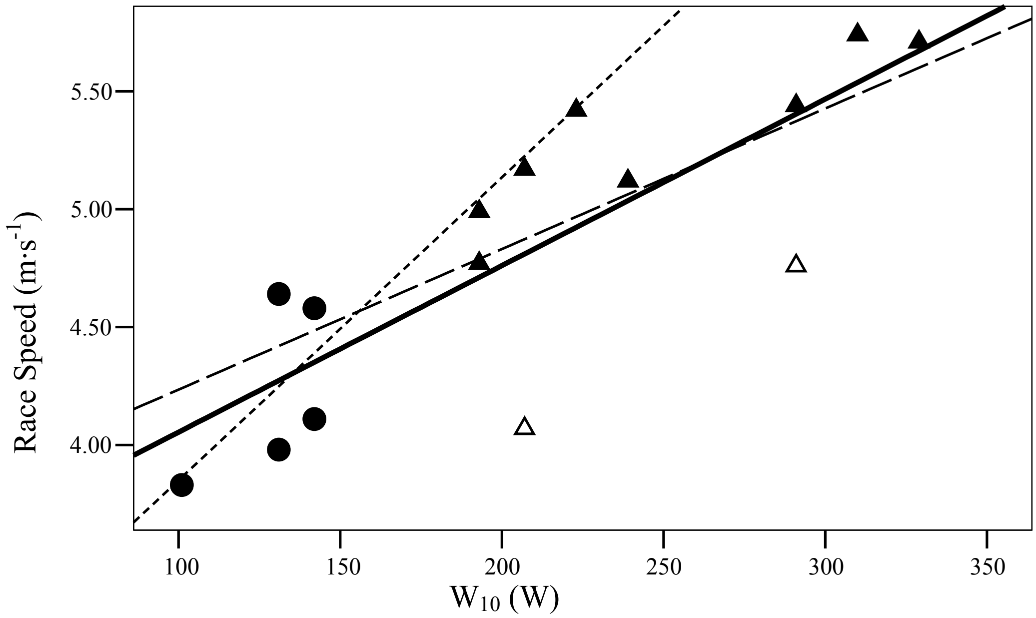

Figure 2. Relationship of race speed to power output from 10-second test (W_{10}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{10} with all subjects (Race Speed = 3.35 + 0.007 x W_{10}; r = .81; SEE = ± 0.38 $m\cdot s^{-1}$). Dashed line is best fit line for W_{10} with women (Race Speed = 2.57 + 0.013 x W_{10}; r = .60; SEE = ± 0.34 $m\cdot s^{-1}$). Broken line is best fit line for W_{10} with men (Race Speed = 3.64 + 0.006 x W_{10}; r = .61; SEE = ± 0.42 $m\cdot s^{-1}$).

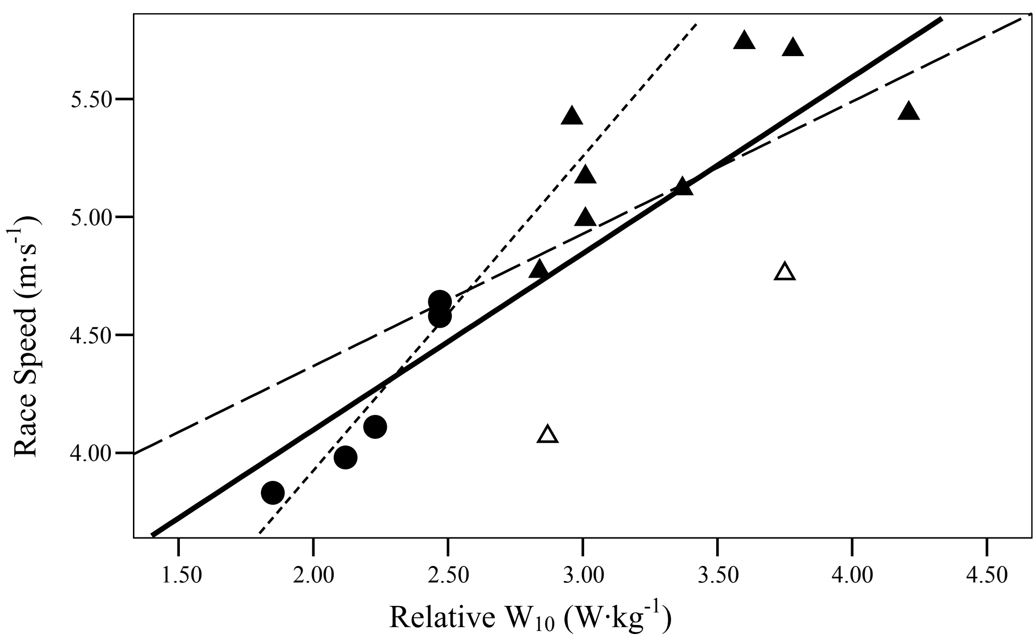

Figure 3. Relationship of race speed to relative power output from 10-second test (W_{10}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{10} with all subjects (Race Speed = 2.6 + 0.748 x W_{10}; r = .81; SEE = ± 0.38 $m\cdot s^{-1}$). Dashed line is best fit line for W_{10} with women (Race Speed = 1.26 + 1.332 x W_{10}; r = .96; SEE = ± 0.12 $m\cdot s^{-1}$). Broken line is best fit line for W_{10} with men (Race Speed = 3.25 + 0.561 x W_{10}; r = .53; SEE = ± 0.46 $m\cdot s^{-1}$).

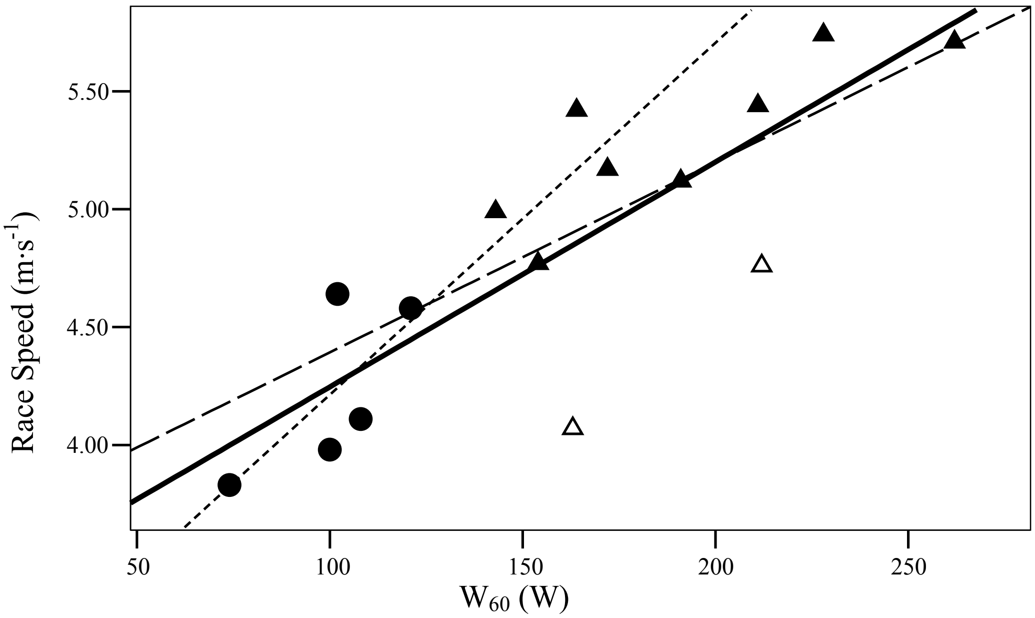

Figure 4. Relationship of race speed to power output from 60-second test (W_{60}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{60} with all subjects (Race Speed = 3.29 + 0.01 x W_{60}; r = .82; SEE = ± 0.37 $m \cdot s^{-1}$). Dashed line is best fit line for W_{60} with women (Race Speed = 2.72 + 0.015 x W_{60}; r = .71; SEE = ± 0.30 $m \cdot s^{-1}$). Broken line is best fit line for W_{60} with men (Race Speed = 3.59 + 0.008 x W_{60}; r = .60; SEE = ± 0.43 $m \cdot s^{-1}$).

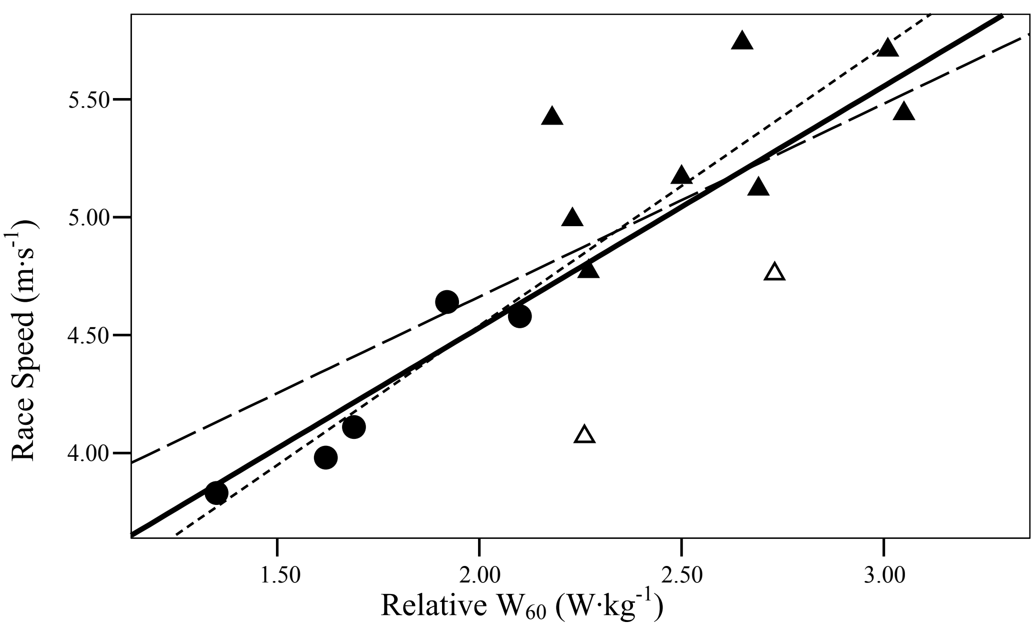

Figure 5. Relationship of race speed to relative power output from 60-second test (W_{60}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{60} with all subjects (Race Speed = 2.48 + 1.024 x W_{60}; r = .82; SEE = ± 0.37 $m \cdot s^{-1}$). Dashed line is best fit line for W_{60} with women (Race Speed = 2.17 + 1.184 x W_{60}; r = .94; SEE = ± 0.15 $m \cdot s^{-1}$). Broken line is best fit line for W_{60} with men (Race Speed = 3.03 + 0.819 x W_{60}; r = .52; SEE = ± 0.46 $m \cdot s^{-1}$).

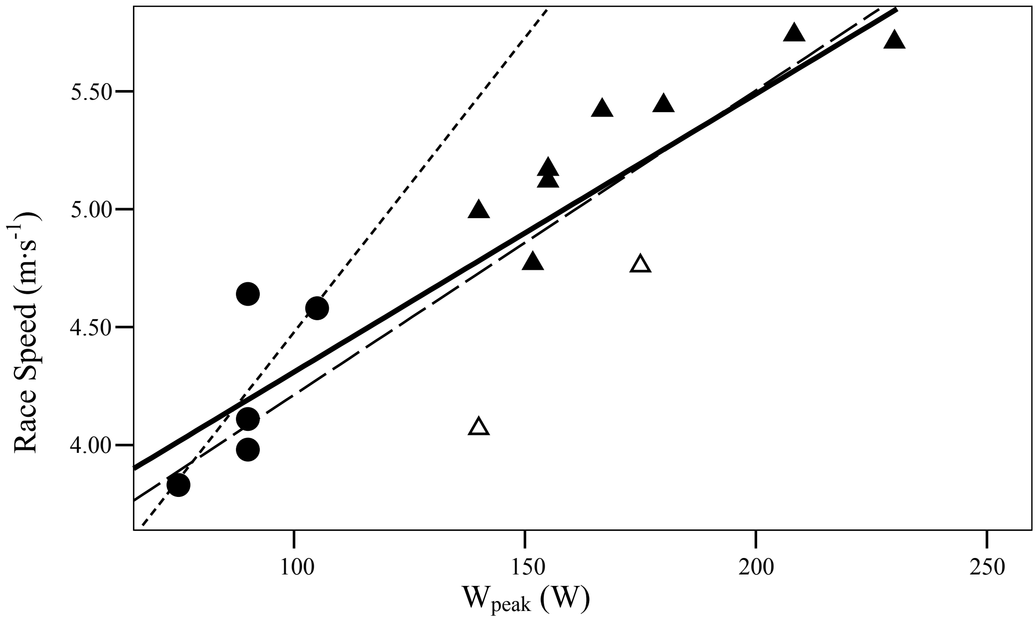

Figure 6. Relationship of race speed to peak power output from incremental test (W_{peak}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{peak} with all subjects (Race Speed = 3.13 + 0.012 x W_{peak}; r = .87; SEE = ± 0.32 $m \cdot s^{-1}$). Dashed line is best fit line for W_{peak} with women (Race Speed = 1.98 + 0.025 x W_{peak}; r = .73; SEE = ± 0.29 $m \cdot s^{-1}$). Broken line is best fit line for W_{peak} with men (Race Speed = 2.92 + 0.013 x W_{peak}; r = .75; SEE = ± 0.35 $m \cdot s^{-1}$).

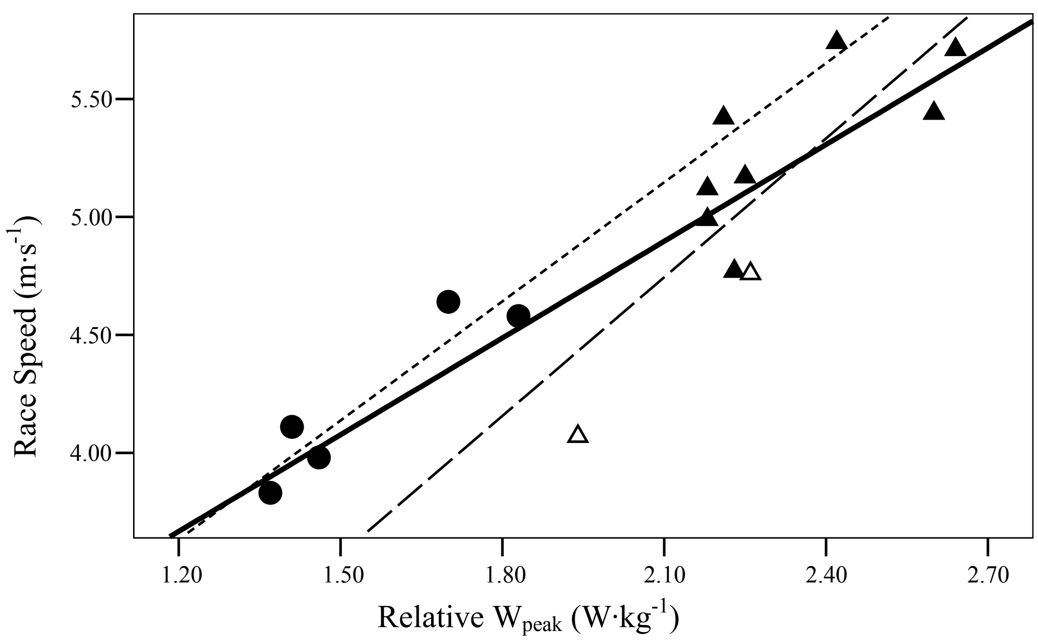

Figure 7. Relationship of race speed to relative peak power output from incremental test (W_{peak}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for W_{peak} with all subjects (Race Speed = 2.03 + 1.367 x W_{peak}; r = .90; SEE = ± 0.28 $m \cdot s^{-1}$). Dashed line is best fit line for W_{peak} with women (Race Speed = 1.61 + 1.68 x W_{peak}; r = .93; SEE = ± 0.15 $m \cdot s^{-1}$). Broken line is best fit line for W_{peak} with men (Race Speed = 0.63 + 1.961 x W_{peak}; r = .81; SEE = ± 0.31 $m \cdot s^{-1}$).

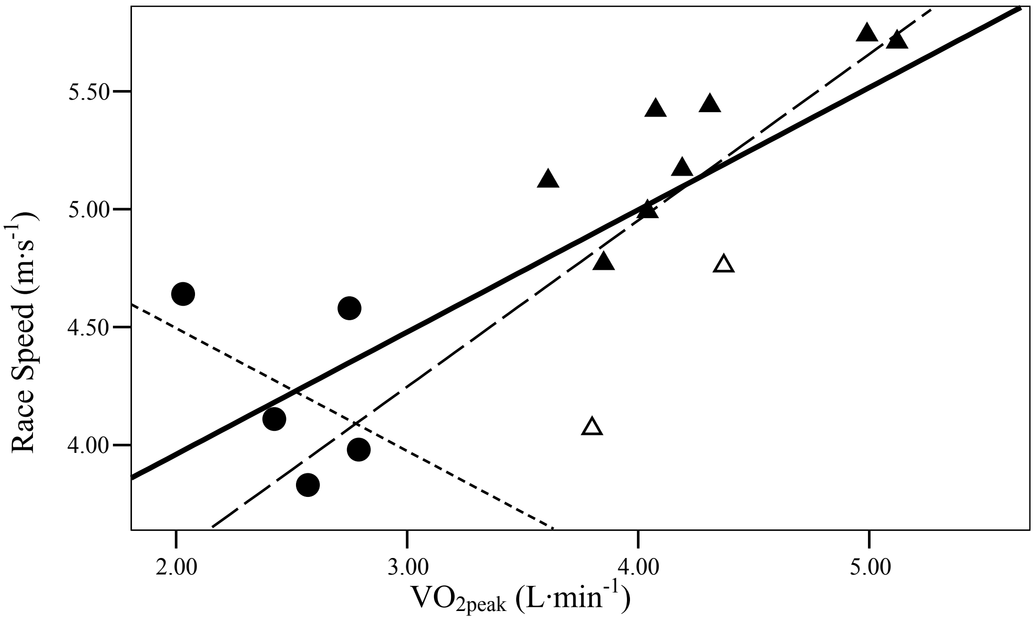

Figure 8. Relationship of race speed to peak oxygen uptake from incremental test (VO_{2peak}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for VO_{2peak} with all subjects (Race Speed = 2.92 + 0.519 x VO_{2peak}; r = .78; SEE = ± 0.40 $m \cdot s^{-1}$). Dashed line is best fit line for VO_{2peak} with women (Race Speed = 5.54 + (-0.521) x VO_{2peak}; r = -.44; SEE = ± 0.38 $m \cdot s^{-1}$). Broken line is best fit line for VO_{2peak} with men (Race Speed = 2.13 + 0.706 x VO_{2peak}; r = .67; SEE = ± 0.39 $m \cdot s^{-1}$).

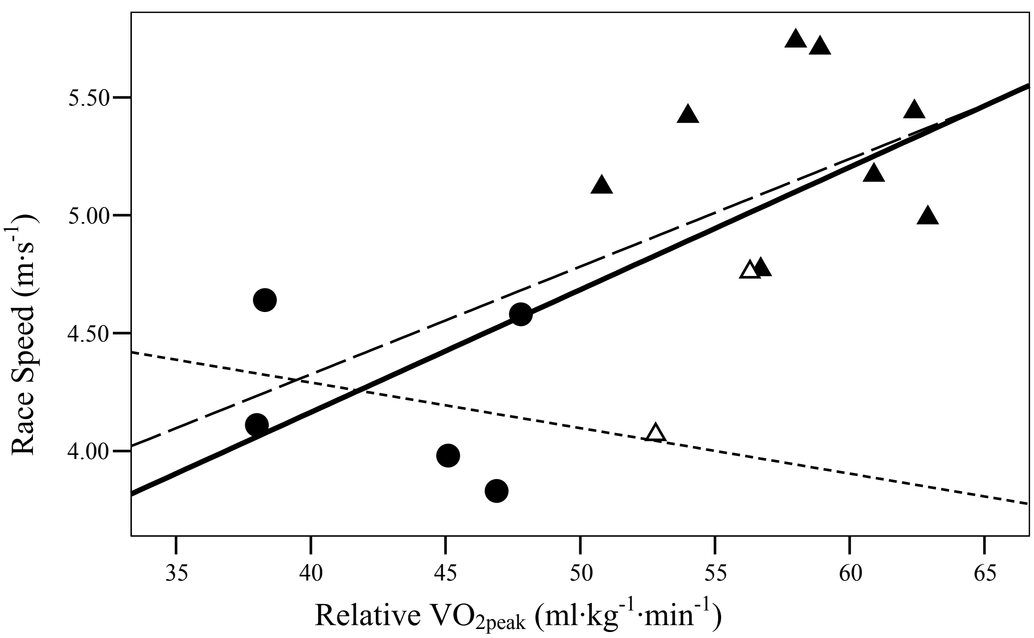

Figure 9. Relationship of race speed to relative peak oxygen uptake from incremental test (VO_{2peak}). Circles represent women (n = 5); triangles represent men (n = 10). Open triangles represent male subjects excluded from subsequent analyses. Solid line is best fit line for VO_{2peak} with all subjects (Race Speed = 2.08 + 0.052 x VO_{2peak}; r = .67; SEE = ± 0.48 $m \cdot s^{-1}$). Dashed line is best fit line for VO_{2peak} with women (Race Speed = 5.06 + (-0.019 x VO_{2peak}; r = -.25; SEE = ± 0.41 $m \cdot s^{-1}$). Broken line is best fit line for VO_{2peak} with men (Race Speed = 2.5 + 0.046 x VO_{2peak}; r = .37; SEE = ± 0.50 $m \cdot s^{-1}$).

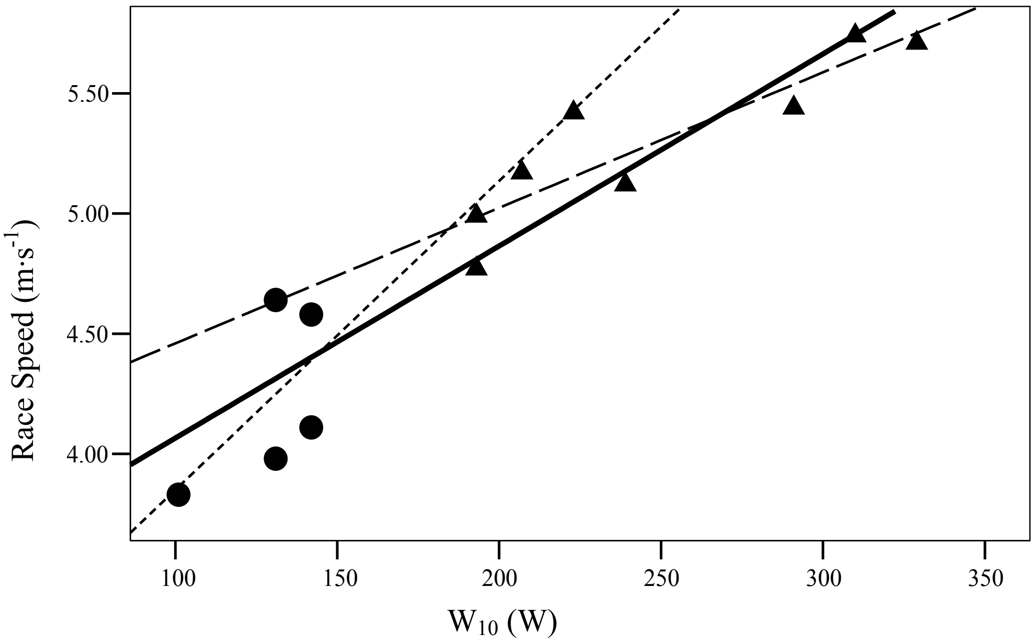

Figure 10. Relationship of race speed to power output from 10-second test (W_{10}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{10} with all subjects (Race Speed = 3.27 + 0.008 x W_{10}; r = .93; SEE = ± 0.25 $m \cdot s^{-1}$). Dashed line is best fit line for W_{10} with women (Race Speed = 2.57 + 0.013 x W_{10}; r = .60; SEE = ± 0.34 $m \cdot s^{-1}$). Broken line is best fit line for W_{10} with men (Race Speed = 3.90 + 0.006 x W_{10}; r = .90; SEE = ± 0.17 $m \cdot s^{-1}$).

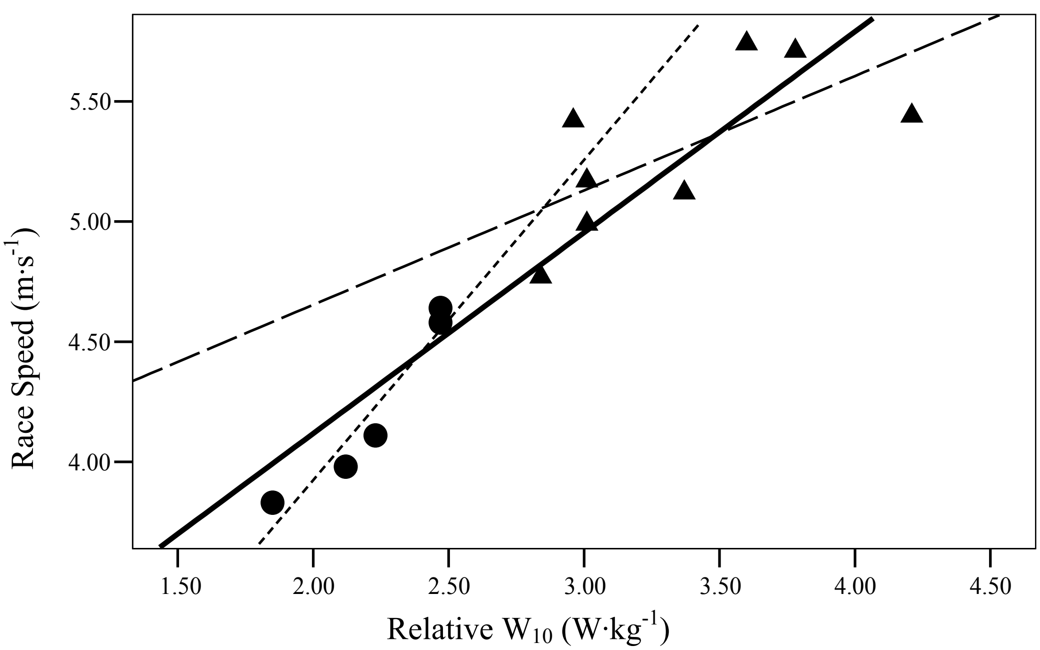

Figure 11. Relationship of race speed to relative power output from 10-second test (W_{10}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{10} with all subjects (Race Speed = 2.45 + 0.836 x W_{10}; r = .91; SEE = ± 0.27 $m \cdot s^{-1}$). Dashed line is best fit line for W_{10} with women (Race Speed = 2.57 + 0.013 x W_{10}; r = .60; SEE = ± 0.34 $m \cdot s^{-1}$). Broken line is best fit line for W_{10} with men (Race Speed = 3.70 + 0.476 x W_{10}; r = .67; SEE = ± 0.27 $m \cdot s^{-1}$).

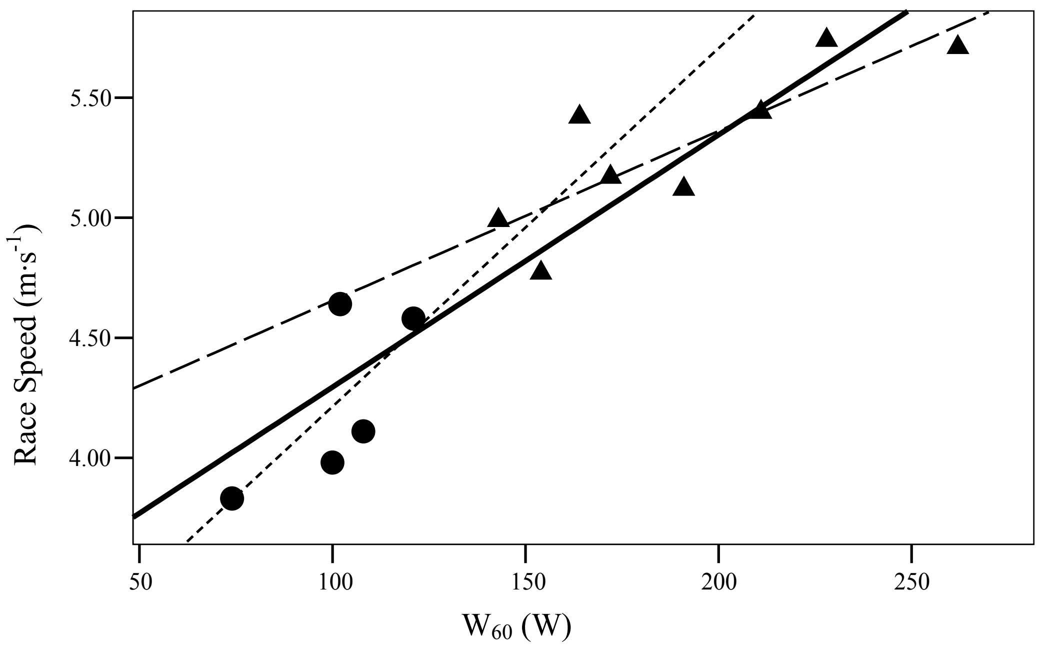

Figure 12. Relationship of race speed to power output from 60-second test (W_{60}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{60} with all subjects (Race Speed = 3.24 + 0.011 x W_{60}; r = .92; SEE = ± 0.25 $m \cdot s^{-1}$). Dashed line is best fit line for W_{60} with women (Race Speed = 2.72 + 0.015 x W_{60}; r = .71; SEE = ± 0.30 $m \cdot s^{-1}$). Broken line is best fit line for W_{60} with men (Race Speed = 3.95 + 0.007 x W_{60}; r = .84; SEE = ± 0.20 $m \cdot s^{-1}$).

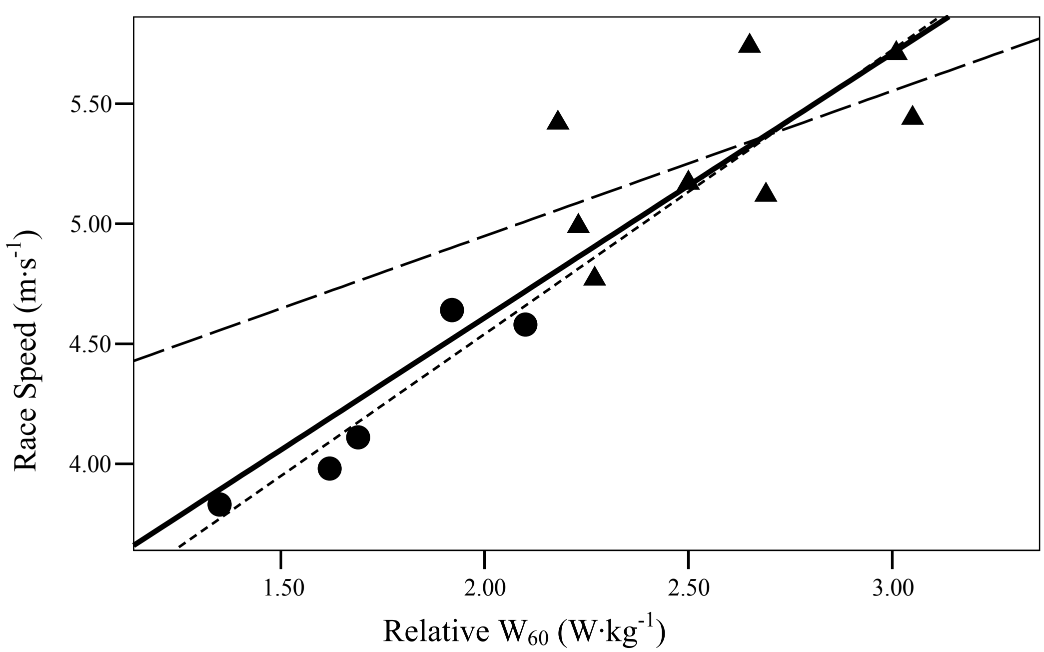

Figure 13. Relationship of race speed to relative power output from 60-second test (W_{60}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{60} with all subjects (Race Speed = 2.41 + 1.102 x W_{60}; r = .91; SEE = ± 0.28 $m \cdot s^{-1}$). Dashed line is best fit line for W_{60} with women (Race Speed = 2.72 + 0.015 x W_{60}; r = .71; SEE = ± 0.30 $m \cdot s^{-1}$). Broken line is best fit line for W_{60} with men (Race Speed = 3.74 + 0.604 x W_{60}; r = .60; SEE = ± 0.30 $m \cdot s^{-1}$).

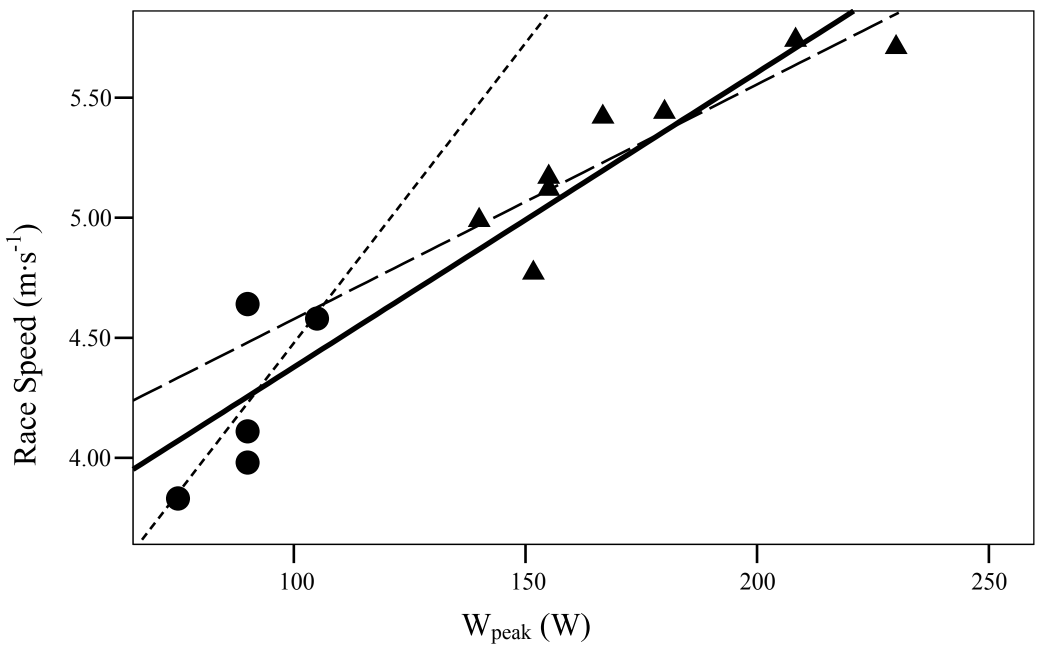

Figure 14. Relationship of race speed to peak power output from incremental test (W_{peak}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{peak} with all subjects (Race Speed = 3.15 + 0.012 x W_{peak}; r = .94; SEE = ± 0.22 $m \cdot s^{-1}$). Dashed line is best fit line for W_{peak} with women (Race Speed = 1.98 + 0.025 x W_{peak}; r = .73; SEE = ± 0.29 $m \cdot s^{-1}$). Broken line is best fit line for W_{peak} with men (Race Speed = 3.6 + 0.010 x W_{peak}; r = .89; SEE = ± 0.17 $m \cdot s^{-1}$).

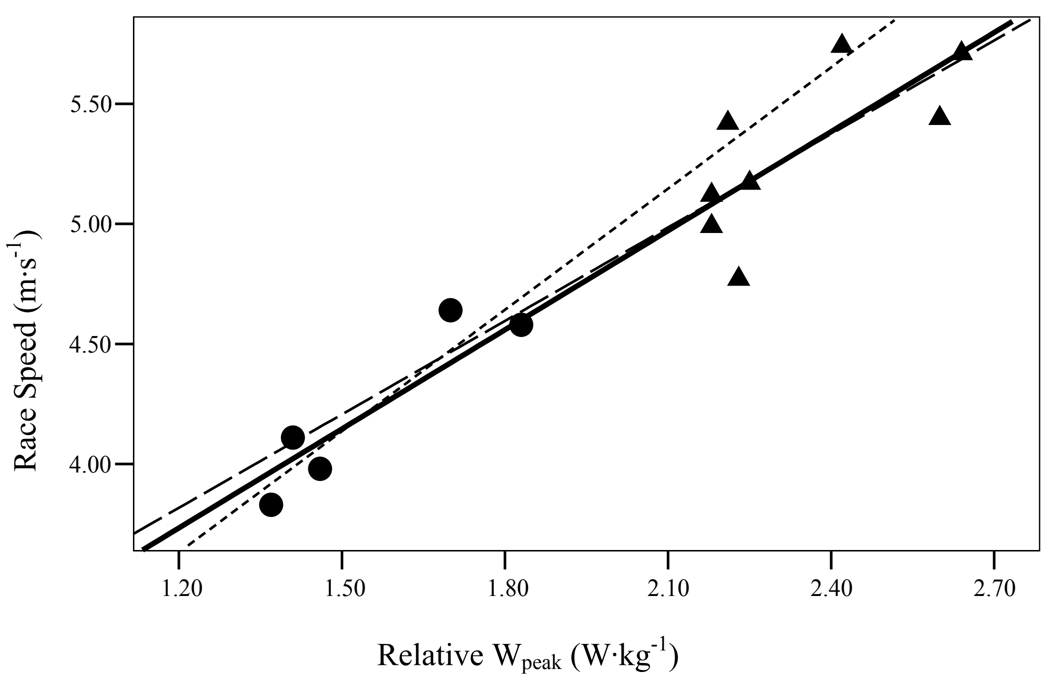

Figure 15. Relationship of race speed to relative peak power output from incremental test (W_{peak}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for W_{peak} with all subjects (Race Speed = 2.08 + 1.375 x W_{peak}; r = .95; SEE = ± 0.21 $m \cdot s^{-1}$). Dashed line is best fit line for W_{peak} with women (Race Speed = 1.98 + 0.025 x W_{peak}; r = .73; SEE = ± 0.29 $m \cdot s^{-1}$). Broken line is best fit line for W_{peak} with men (Race Speed = 2.26 + 1.298 x W_{peak}; r = .72; SEE = ± 0.26 $m \cdot s^{-1}$).

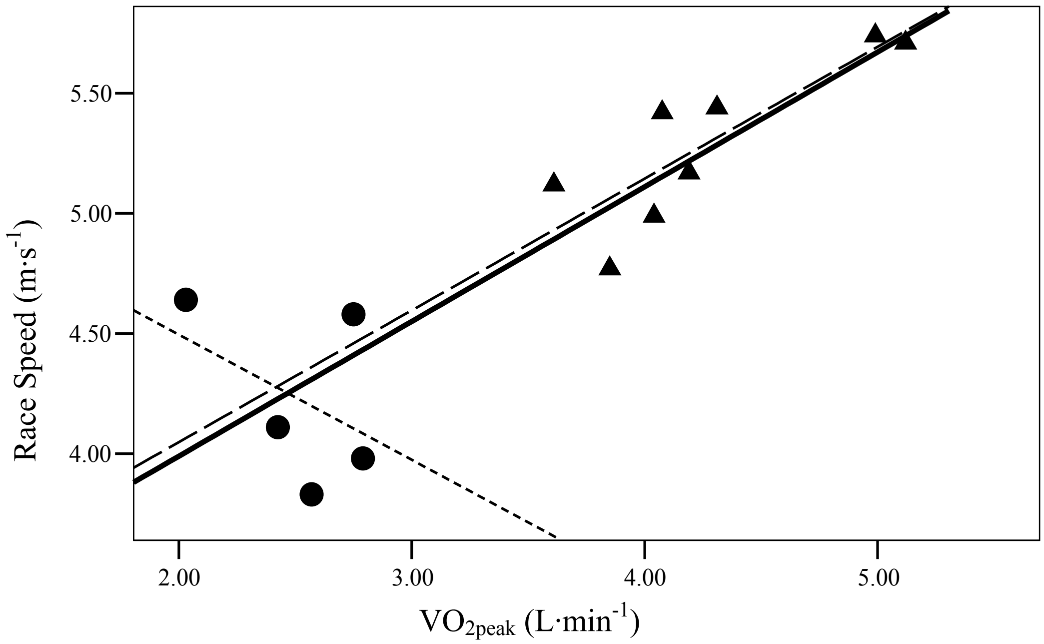

Figure 16. Relationship of race speed to peak oxygen uptake from incremental test (VO_{2peak}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for VO_{2peak} with all subjects (Race Speed = 2.87 + 0.561 x VO_{2peak}; r = .88; SEE = ± 0.32 $m \cdot s^{-1}$). Dashed line is best fit line for VO_{2peak} with women (Race Speed = 5.54 + (-0.521) x VO_{2peak}; r = -.44; SEE = ± 0.38 $m \cdot s^{-1}$). Broken line is best fit line for VO_{2peak} with men (Race Speed = 2.95 + 0.549 x VO_{2peak}; r = .85; SEE = ± 0.20 $m \cdot s^{-1}$).

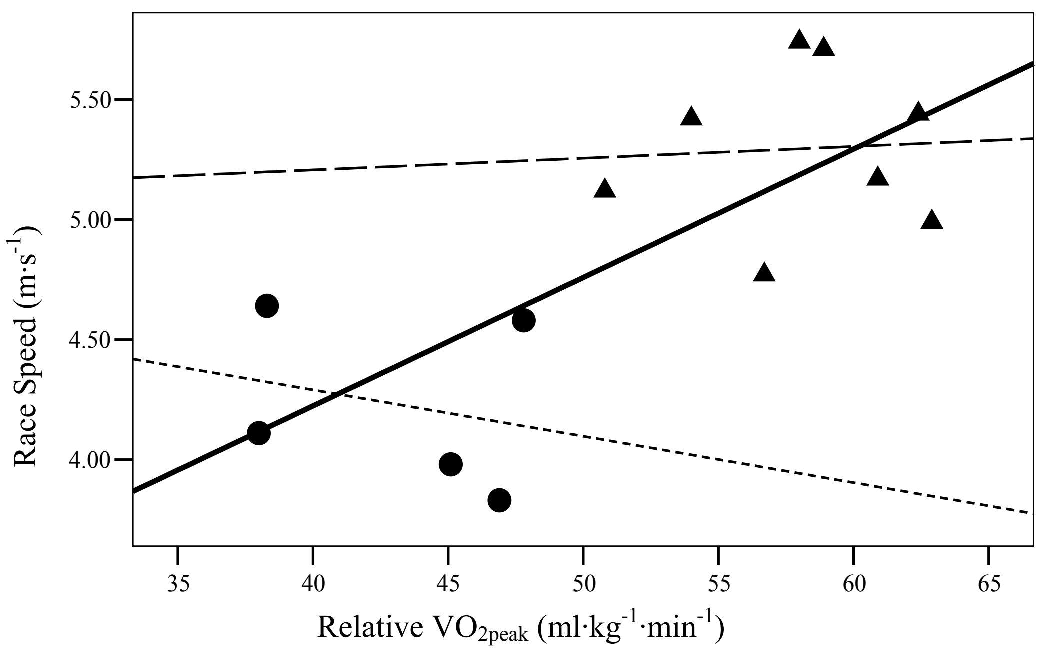

Figure 17. Relationship of race speed to relative peak oxygen uptake from incremental test (VO_{2peak}). Circles represent women (n = 5); triangles represent men (n = 8). Solid line is best fit line for VO_{2peak} with all subjects (Race Speed = 2.08 + 0.053 x VO2peak; r = .73; SEE = ± 0.46 $m \cdot s^{-1}$). Dashed line is best fit line for VO_{2peak} with women (Race Speed = 5.54 + (-0.521) x VO_{2peak}; r = -.44; SEE = ± 0.38 $m \cdot s^{-1}$). Broken line is best fit line for VO_{2peak} with men (Race Speed = 5.01 + 0.005 x VO_{2peak}; r = .06; SEE = ± 0.37 $m \cdot s^{-1}$).