THE EFFECTS OF HIP ANGLE MANIPULATION ON SUBMAXIMAL OXYGEN CONSUMPTION IN COLLEGIATE CYCLISTS

by

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ABSTRACT

The purpose of this study was to determine the effects of hip angle (HA) manipulation on submaximal oxygen consumption ($\dot{V}O_{2SUB}$) in collegiate cyclists. Sixteen collegiate cyclists (Mean±SD; 23.3±3.5 years; 73.3±5.9 kg body mass; 4.54±0.34 L/min $\dot{V}O_{2MAX}$) were tested in five positions, each resulting in a different HA, on a cycling ergometer. The positions tested were centered around the mean HA corresponding to each cyclist's preferred position (P_0), defined as the combination of trunk angle (TA) and seat tube angle (STA) in which each cyclist self-reported spending most of their time training on a bicycle. The five positions tested were the cyclist's P_0 and positions resulting in mean HA's of +10º, +5º, -5º, and -10º relative to their P_0. All cyclists were tested in each of the positions at a power output corresponding to 85% of ventilatory threshold. Sagittal-view kinematics for mean HA, TA, knee angle (KA) and ankle angle (AA) were recorded to confirm that HA was the only positional measurement being manipulated. Kinematic measures confirmed that mean TA, KA, and AA were not significantly different ($P>0.05$). Furthermore, it was confirmed that all HA's were significantly different ($P>0.05$) except between the positions +5º and +10º greater than that that corresponding to P_0. No significant differences were found when comparing $\dot{V}O_{2SUB}$ ($P>0.05$), heart rate ($P>0.05$), or minute ventilation ($\dot{V}_e$; $P>0.05$) across the five positions. Non-significant quadratic trends were found for all three physiological measures across the five positions. It appears that $\dot{V}O_{2SUB}$, HR, and $\dot{V}_e$ are all minimized at positions equivalent to P_0 or +5º greater than that corresponding to P_0. In the population tested, it appears that "cross training" may alter the relationship between $\dot{V}O_{2SUB}$ and HA's greater than that corresponding to P_0, thereby limiting comparison to a professional cyclist. The lack of significant differences between conditions indicates that the prediction algorithm created by Klippel and Heil (2001) may not be applicable to recreationally trained cyclists. According to the revised algorithm, a position that reduces TA, and therefore HA, results in a time trial position that maximizes ground speed for a majority of the collegiate cyclists tested.

CHAPTER 1

INTRODUCTION

Success in many road cycling competitions is due, in part, to time-trialing ability. Time-trialing is a form of cycling competition that requires a cyclist to ride alone over a set distance (usually between 20 and 40 kms) as fast as possible. The main goal for a cyclist in this discipline is to maintain the highest average speed possible.

Advanced training knowledge suggests that time-trialing is a direct representation of a cyclist's overall conditioning. In the past twenty years, many new training devices have been developed to explain and improve time-trialing ability. Power measuring devices, for example, incorporated into either the crank arms or rear hub of the bicycle, represent the most successful attempt to quantify time-trial performance by means of quantifying the gross power production, in watts, of the cyclist. Subsequently, researchers have shown that increased power output at a cyclist's ventilatory threshold ($\dot{W}_{VT}$, watts) correlates with improved time-trial performances (Coyle et al., 1991). Ventilatory threshold (VT) is defined by Myers and Ashley (1997) as the point at which lactate begins to accumulate in the blood, causing an increase in ventilation. In addition, several researchers have shown a high degree of correlation between time-trial performance and aerobic peak power output ($\dot{W}_{PEAK}$, watts), defined as the maximum power output achieved by a cyclist during an incrementally graded exercise test to exhaustion (Balmer, Davison, & Bird, 2000; Bentley, McNaughton, Thompson, Vleck, & Batterham, 2001; Bishop, Jenkins, & Mackinnon, 1998; Hawley & Noakes, 1992).

The external forces that attempt to slow a cyclist's forward movement are rolling resistance, frictional resistance, gravitational resistance, and aerodynamic drag (Bassett, Kyle, Passfield, Broker, & Burke, 1999; Candau et al., 1999; Di Prampero, Cortili, Mognoni, & Saibene, 1979; Groot et al., 1994; Olds, 2001; Olds, Norton, Craig, Olive, & Lowe, 1995; Pons & Vaughan, 1989, Whitt, 1971). Aerodynamic drag represents the majority of resistance experienced by a cyclist on level terrain at speeds common in elite-level time-trials (Candau et al., 1999; Groot et al., 1994; Olds, 2001). Competitive cyclists are placing more importance on the reduction of aerodynamic drag when determining their time-trial position. A majority of the advances in decreasing aerodynamic drag have focused on decreasing frontal area. Experts have generally formed two opinions on aerodynamic positioning. Among traditional road cyclists, frontal area is decreased by a reduction in the cyclist's trunk angle (TA, degrees), the angle between a horizontal line and one intersecting both the hip and shoulder joints (Figure 1, Figure 2). Consequently, the cyclist's mean hip angle (HA, degrees), the angle between the thigh and torso (Figure 1, Figure 2), will also decrease. However, this position does maintain both seat height (SH, cm), the distance between the center of the bottom bracket and the top of the saddle, and seat tube angle (STA, degrees), the angle between the seat tube and a horizontal line (Figure 1, Figure 2). Among competitive triathletes, frontal area is decreased by effectively rotating the cyclist's position relative to the bottom bracket by using a steeper STA as depicted in Figures 1 and 3. Maintaining the cyclist's HA, in combination with the steeper STA of this position, results in a position that decreases both TA and frontal area. While the aerodynamic benefits of this position are less than that used by traditional road cyclists, mean HA is maintained (Heil, Derrick, & Whittlesey, 1997).

Most competitive cyclists train 600-1200 hours per year, a majority of which are spent in the cyclist's preferred position (P_0). The P_0 is defined as the combination of TA and STA in which cyclists spend most of their time training on a bicycle. The P_0 will have a training effect on the muscles of the lower limbs, hip extensors, and lower back muscles resulting in muscle lengths in which power production is maximized.

Heil et al. studied the consequences of manipulating a cyclist's mean HA (Heil, Derrick et al., 1997; Heil et al., 1995; Price & Donne, 1996; Too, 1991, 1994). Both Heil et al. and Price et al. found, in general, that metabolic measurements, such as oxygen consumption, were minimized when mean HA approached that corresponding to P_0 (Heil et al., 1997; Price & Donne, 1997). Too (1991, 1994) found a change in anaerobic $\dot{W}_{PEAK}$ when HA was manipulated; decreases in anaerobic $\dot{W}_{PEAK}$ should correspond to a decreased aerobic $\dot{W}_{PEAK}$ and $\dot{W}_{VT}$. The result would be an increased metabolic cost in order to maintain any power output at or below $\dot{W}_{VT}$ (Heil, Derrick, and Whittlesey, 1997). To the present author's knowledge, there has been no published research establishing a direct relationship between P_0 and $\dot{W}_{VT}$.

If changes in HA corresponding to a cyclist's P_0 result in a decrease in $\dot{W}_{VT}$, it should be possible to mathematically predict, through simulation, a cyclist's optimal aerodynamic position for time-trial racing (Klippel and Heil, 2002). Using a cyclist's $\dot{W}_{VT}$ in their P_0, and body mass (M_B), the proposed algorithm would predict the STA and TA that resulted in the optimal balance of both aerodynamic drag and power production.

The outcome of this algorithm would be a time-trial position that potentially maximized the speed of the cyclist.

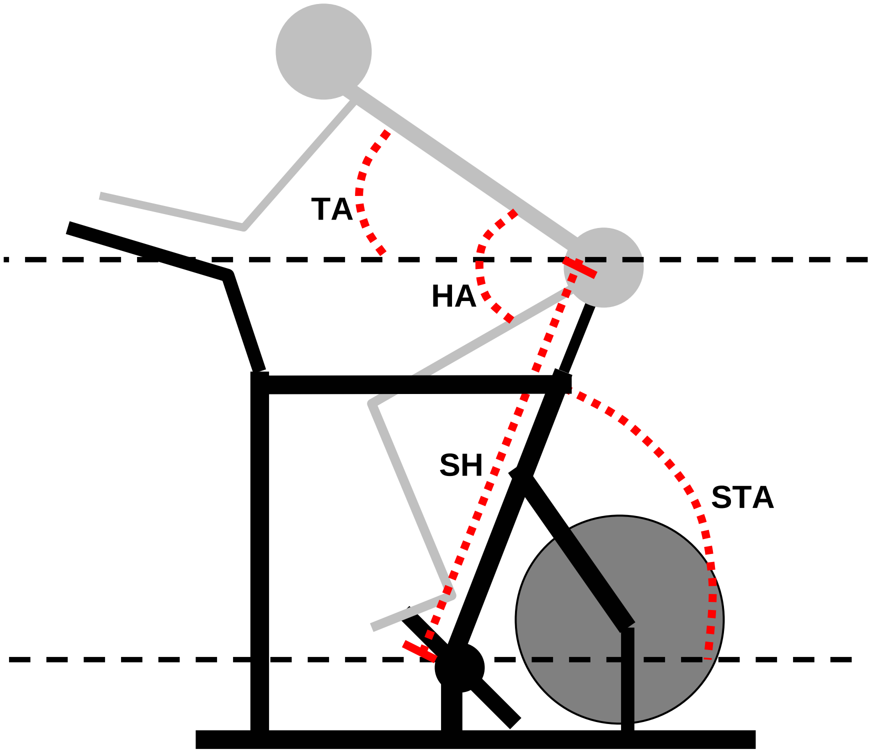

Figure 1. Cycle ergometer used to modify body position. Trunk angle (TA) is defined as the angle between a horizontal line and another one intersecting both the hip and shoulder joints. Hip angle (HA) is defined as the mean angle between the thigh and torso. Seat height (SH) is defined as the distance between the center of the bottom bracket and the top of the saddle. Seat tube angle (STA) is defined as the angle between the seat tube and a horizontal line.

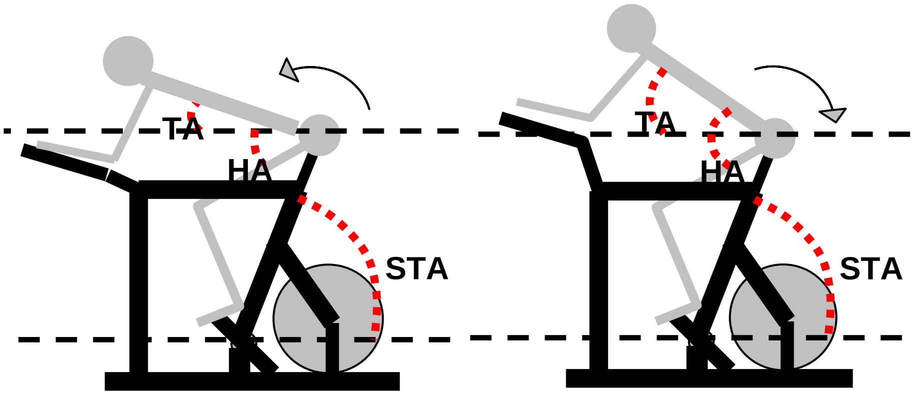

Figure 2. Aerodynamic positioning. Trunk angle (TA) decreases, and, as a result, frontal area decreases. Hip angle (HA) decreases. Seat tube angle (STA) remains stable.

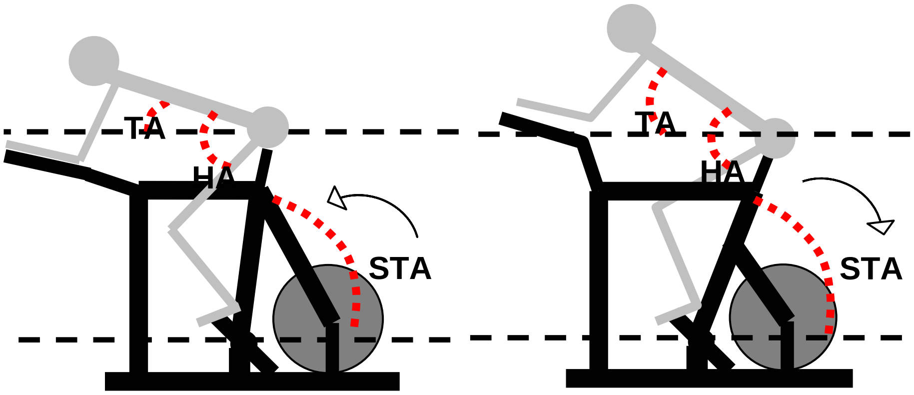

Figure 3. Aerodynamic positioning. Seat tube angle (STA) increases, rotating the cyclist forward around the bottom bracket. Trunk angle (TA) decreases, and, as a result, frontal area decreases. Hip angle (HA) remains stable.

Statement of the Problem

The relationship between submaximal oxygen consumption ($\dot{V}O_{2SUB}$, $ml \cdot kg^{-1} \cdot min^{-1}$) and a cyclist's preferred position (P_0) had not been systematically explored. To substantiate the algorithm created by Klippel and Heil (2002), there was a need to determine whether the mean hip angle (HA) corresponding to a cyclist's P_0 elicited the lowest $\dot{V}O_{2SUB}$ at a fixed power output, as suggested by Heil et al. (1997).

Purpose

The purpose of this study was to evaluate the relationship between P_0 and $\dot{V}O_{2SUB}$ in competitive cyclists. Specifically, this study was designed to systematically determine if the HA corresponding to a cyclist's P_0 minimized $\dot{V}O_{2SUB}$ at a fixed power output, as suggested by Heil et al. (1997).

Hypothesis

It was hypothesized that $\dot{V}O_{2SUB}$ would increase as HA was either increased or decreased from the HA corresponding to a cyclist's P_0 while cycling at a constant power output.

$$H_O : \mu_{+10} = \mu_{+5} = \mu_0 = \mu_{-5} = \mu_{-10}$$

$$H_A : \mu_{+10} > \mu_{+5} > \mu_0 < \mu_{-5} < \mu_{-10}$$

Where: $\mu_0 = \dot{V}O_{2SUB}$ at a HA corresponding to P_0

$\mu_{+10} = \dot{V}O_{2SUB}$ at a HA corresponding to P_{+10}

$\mu_{+5} = \dot{V}O_{2SUB}$ at a HA corresponding to P_{+5}

$\mu_{-10} = \dot{V}O_{2SUB}$ at a HA corresponding to P_{-10}

$\mu_{-5} = \dot{V}O_{2SUB}$ at a HA corresponding to P_{-5}

Delimitations

This study was delimited to trained collegiate road cyclists and to the range of HAs evaluated.

Limitations

The study sample consisted of trained collegiate cyclists.

Significance of Study

The focus of this study was to determine whether the HA corresponding to P_0 resulted in the lowest $\dot{V}O_{2SUB}$ for a given power output and if the relationship between P_0 and $\dot{V}O_{2SUB}$ differed from the quadratic relationship reported by Heil et al. (1997). The resultant relationship between P_0 and $\dot{V}O_{2SUB}$ would be used to update Klippel and Heil's (2002) algorithm, providing a more accurate estimation of a cyclist's optimal position. If the HA corresponding to a cyclist's P_0 resulted in the lowest $\dot{V}O_{2SUB}$ at a given power output, then further study would be warranted to determine whether cyclists were able to train their musculature to reduce oxygen consumption in alternative positions.

Operational Definitions

Aerobars:	Handlebar attachments that allow a cyclist to support their upper body on their elbows with forearms pointing forward, placing the cyclist in a position similar to a downhill ski racer's tuck position.
Aerodynamic Resistance:	The resistance encountered by a cyclist from friction between the cyclist and air flow around the cyclist.
AA:	Ankle Angle; defined as the mean acute angle (degrees) between a line intersecting the knee and ankle joints and

	another one intersecting the ankle joint and the most distal part of the cyclist’s shoe.
Bicycle Geometry:	The combination of trunk angle (TA), seat height (SH), and seat tube angle (STA) that are used to create a position for the cyclist.
M_B:	Body Mass; the mass (kg) of the cyclist including clothes and shoes.
Frictional Resistance:	The resistance encountered by a cyclist from friction produced by wheel and pedal bearings.
Frontal Area:	The combined frontal surface area (m^2) of the cyclist and bicycle.
Gravitational Resistance:	The resistance encountered by a cyclist from gravity; the result of vertical work.
HA:	Mean Hip Angle; defined as the mean acute angle (degrees) between the thigh and the torso for one pedal revolution (Figure 1).
KA:	Knee Angle; defined as the mean acute angle (degrees) between the thigh and lower leg for one pedal revolution.
Position:	The combination of a specific trunk angle (TA) and seat tube angle (STA).

P_0:	Preferred Position; the combination of trunk angle (TA) and seat tube angle (STA) in which cyclists spend most of their time training on a bicycle.
P_{+5}:	The position resulting in a mean hip angle (HA) five degrees greater than the HA corresponding to P_0 while maintaining the cyclist's lower limb kinematics.
P_{-5}:	The position resulting in a mean hip angle (HA) five degrees less than the HA corresponding to P_0 while maintaining the cyclist's lower limb kinematics.
P_{+10}:	The position resulting in a mean hip angle (HA) ten degrees greater than the HA corresponding to P_0 while maintaining the cyclist's lower limb kinematics.
P_{-10}:	The position resulting in a mean hip angle (HA) ten degrees less than the HA corresponding to P_0 while maintaining the cyclist's lower limb kinematics.
P_{OPTIMAL}:	Optimal Position; the position that minimizes frontal area while maintaining $\dot{W}_{VT}$.
RPE:	Rate of perceived exertion; a rating of the perceived exertion a subject feels they are experiencing according to either the category or category-ratio scale.
Rolling Resistance:	The resistance encountered by cyclist from friction produced between the rolling surface and the bicycle tire.

SH:	Seat Height; the distance, in centimeters, between the center of the bottom bracket and the top of the saddle (Figure 1).
STA:	Seat Tube Angle; the acute angle (degrees) between the seat tube and a horizontal line (Figure 1).
TA:	Trunk Angle; the acute angle (degrees) between a horizontal line and another one intersecting the hip and shoulder joints (Figure 1).
Time-trial:	A cycling competition where cyclists race over a fixed distance in the fastest time possible.
$\dot{V}O_2$:	Oxygen Consumption, measured in both absolute terms (L/min) and relative terms ($ml \cdot kg^{-1} \cdot min^{-1}$); the rate of oxygen consumed.
$\dot{V}O_{2MAX}$:	Maximal Oxygen Consumption, measured in both absolute terms (L/min) and relative terms ($ml \cdot kg^{-1} \cdot min^{-1}$); the maximal rate of oxygen a subject can consume during aerobic exercise.
$\dot{V}O_{2LACTATE}$:	Oxygen Consumption at Lactate Threshold; oxygen consumption measured in $ml \cdot kg^{-1} \cdot min^{-1}$ corresponding to ventilatory, and, correspondingly, lactate threshold.
$\dot{V}O_{2SUB}$:	Steady-state Submaximal Oxygen Consumption; measured in $ml \cdot kg^{-1} \cdot min^{-1}$, corresponding to any oxygen consumption at a level less than maximal.

VT:	Ventilatory Threshold; defined by Myers and Ashley (1997) as the point at which lactate begins to accumulate in the blood, causing an increase in ventilation.
$\dot{W}_{PEAK}$:	Aerobic Peak Power Output; the maximum power output (watts) achieved by a cyclist as a result of an incrementally graded exercise test to exhaustion.
$\dot{W}_{PP}$:	Anaerobic Peak Power Output; the maximum power output (watts) achieved by a cyclist during a Wingate cycling test.
$\dot{W}_{VT}$:	Power Output at Ventilatory Threshold; the highest power output (watts) a cyclist can sustain at their ventilatory threshold; for the purposes of this study, equivalent to power output at lactate threshold.

CHAPTER 2

LITERATURE REVIEW

Energy Supply And Demand

Time-trial cycling is best explained in terms of a supply and demand relationship. The speed a cyclist is capable of achieving is proportional to the amount of energy produced. Maximum speed is attained when energy demand is exactly equivalent to the energy supply. Any attempts to increase the maximal achievable speed of a cyclist must either increase the maximal amount of energy that can be supplied, power supply, or decrease the amount of energy that is being required, power demand. The energy supply of bicycle racing is equivalent to the cumulative physiological power output. The energy demands of bicycle racing are divided into four discrete components that comprise the net resistance to forward motion: gravitational, frictional, rolling, and aerodynamic resistance (Candau et al., 1999; Di Prampero et al., 1979; De Groot et al., 1994; Olds et al., 1995; Olds, 2001; Whitt, 1971). Each of these four elements is now examined with specificity to the type of cycling being researched, time-trial racing on level terrain.

Frictional Resistance

One type of resistance encountered by a racing cyclist is the friction produced by wheel and pedal bearings (Di Prampero et al., 1979; Whitt, 1971). According to Whitt, the frictional resistance of the wheel bearings is insignificant. The power loss attributed to frictional resistance is estimated to be less than 5% of the total resistance experienced by a time-trial cyclist (Pons & Vaughan, 1989).

Gravitational Resistance

Olds (2001) defined gravitational resistance as a function of the grade of the surface being used. According to Di Prampero et al. (1979), additional resistance from the effects of gravity are only added to the total resistance of a cyclist when the surface being used has a measurable angle (i.e., greater than zero degrees). The mode of bicycle racing being researched was time-trialing on level terrain, therefore gravitational resistance comprised a negligible portion of the total energy demand.

Rolling Resistance

Rolling resistance accounts for a small amount of the total resistance encountered by a cyclist on a flat course. The two main components of rolling resistance are the mass of the cyclist and the coefficient of friction between the rolling surface and the bicycle tire. The coefficient of friction is affected by a large number of factors: the width of the tire, the size of the wheel, the type of road surface, the inflation pressure of the tire, and the material characteristics of the tire (Di Prampero et al., 1979; Olds, Norton, Craig, et al., 1995; Olds, 2001; Whitt, 1971).

Aerodynamic Resistance

Aerodynamic resistance is the greatest of the resistive forces experienced by a cyclist on a level surface (De Groot et al., 1994; Olds, 2001). Candau et al. (1999) found that aerodynamic resistance accounts for about 90% of the total resistance to forward motion. Aerodynamic equipment such as lycra skinsuits, tear-drop helmets, and disc or aero-spoked wheels, all characterized by surface smoothness, decrease aerodynamic resistance by reducing the surface drag of a rider (Burke, 1995). However, the largest reduction in aerodynamic drag is realized through a decrease in frontal area of the cyclist, which directly corresponds to a drop in pressure drag (Bassett et al., 1999; Di Prampero et al., 1979; Olds et al., 1995; Olds, 2001; Whitt, 1971). Pressure drag is the delta of high pressure as measured in the front of the cyclist and the area of low pressure measured behind (Burke, 1995). Jeukendrup and Martin (2001) proposed that the time gains realized by reducing the frontal area of a cyclist during a 40 km time-trial could range from 2 min 47 sec for riding in the handlebar drops to 6 min 54 sec for an optimized aerodynamic position. In the 2002 World Road Cycling Championships, 6 min 54 sec would nearly account for the total difference between first and last place (57th, - 6 min 57 sec).

Olds (2001) reported that when gravitational and kinetic energy demands were eliminated from the supply-demand equation, the remaining relationship was:

$$\text{Total}_{\text{ExternalDemand}} = \text{Resistance}_{\text{Aerodynamic}} + \text{Resistance}_{\text{Rolling}} \tag{1}$$

where $\text{Total}_{\text{ExternalDemand}}$ = the sum of all external resistive forces to forward motion, $\text{Resistance}_{\text{Aerodynamic}}$ = aerodynamic resistance, and $\text{Resistance}_{\text{Rolling}}$ = rolling resistance. On the assumption that if 1) frictional resistance is negligible, 2) gravitational resistance is negligible (with no measurable grade), and 3) the cyclist is maintaining a relatively consistent speed, then Olds' equation will be an accurate description of the energy supply-demand relationship during time-trial cycling.

Performance Measures

In the exploration of performance measures, power output has been shown by various studies to correlate best with performance. If all physiological measures are considered, power output is the cumulative output of the physiological power supply.

Two measures of power commonly used to explain the relationship between power output and endurance performance are peak power output ($\dot{W}_{PEAK}$, watts) and power output at ventilatory threshold ($\dot{W}_{VT}$, watts). Hawley and Noakes (1992) defined $\dot{W}_{PEAK}$ as “the highest exercise intensity the subject completed” during a maximal test. While both $\dot{W}_{PEAK}$ and $\dot{W}_{VT}$ have correlated significantly with performance (Balmer et al., 2000; Bentley et al., 2001; Bishop, Jenkins, & MacKinnon, 1998; Coyle et al., 1991; Hawley & Noakes, 1992) they are not the same measure. Both $\dot{W}_{PEAK}$ and maximal oxygen consumption ($\dot{V}O_{2MAX}$) are indicators of a cyclist’s maximal pace, while $\dot{W}_{VT}$ and oxygen consumption at lactate threshold ($\dot{V}O_{2LACTATE}$) are indicators of a cyclist’s maximal sustainable pace. In athletes with similar $\dot{W}_{PEAK}$ and $\dot{V}O_{2MAX}$ values, the best measures of performance are $\dot{W}_{VT}$ and work rate at $\dot{V}O_{2LACTATE}$.

Coyle et al. (1991) attempted to define the role of physiological measures in elite cycling performance. They enlisted 15 elite and state-level cyclists to complete a one-hour laboratory time-trial while various physiological and biomechanical measures were recorded. As a result of the homogeneous nature of the population tested, comprising only elite and state level cyclists, $\dot{V}O_{2MAX}$ values were similar. Coyle et al. found that $\dot{V}O_{2LACTATE}$ was highly correlated with $\dot{W}_{VT}$ measured during the one-hour laboratory test (r = 0.93). The results of this laboratory test were then compared to the cyclists' best 40 km time-trial time during the previous 12 months. When analyzed using forward multiple regression techniques, $\dot{W}_{VT}$ was the most significant predictor of time-trial performance times. Coyle et al. found that cyclists with the highest $\dot{W}_{VT}$ during the laboratory test had the lowest 40 km time-trial times (r = –0.88). Given that the population tested was similar in both training experience and $\dot{V}O_{2MAX}$ values, it should be expected that $\dot{W}_{VT}$ will best predict time-trial performance.

The importance of power production to cycling performance was reinforced by the research of Hawley and Noakes (1992). In the one hundred male and female cyclists initially tested, $\dot{V}O_{2MAX}$ and $\dot{W}_{PEAK}$ were highly correlated (r = 0.97). Nineteen of the one hundred cyclists were individually tested to determine the relationship between $\dot{W}_{PEAK}$ and 20 km time-trial time. A close correlation was found between $\dot{W}_{PEAK}$ and 20k time-trial time (r = –0.91). The researchers concluded that $\dot{W}_{PEAK}$ was a better predictor of cycling time-trial performance than other commonly measured physiological variables. The subjects tested were recreationally trained cyclists with heterogeneous training backgrounds, not only competitive cyclists. Consequently, the relationship between $\dot{W}_{PEAK}$ and performance can be likened to that between $\dot{V}O_{2MAX}$ and cycling time-trial performance. If the population being tested had consisted entirely of trained cyclists, presumably the correlation between the $\dot{W}_{PEAK}$ and performance would have decreased.

Balmer et al. (2000) found that $\dot{W}_{PEAK}$ correlated closely with $\dot{W}_{VT}$ during a 16.1 km time-trial (r = 0.97). Nine local, trained cyclists were tested on two separate occasions. The first testing session consisted of an incremental laboratory cycling test to determine $\dot{W}_{PEAK}$. The second consisted of an outdoor 16.1 km time-trial to determine $\dot{W}_{VT}$. It may be observed that when the subjects' heterogeneous training backgrounds are taken into consideration, the positive relationship identified between $\dot{W}_{PEAK}$ and $\dot{W}_{VT}$ was to be expected, as $\dot{V}O_{2MAX}$ would also correlate highly with $\dot{V}O_{2LACTATE}$ in a similar group.

Bentley et al. (2001) found that a relationship existed between $\dot{W}_{PEAK}$ and $\dot{W}_{VT}$ for longer time periods. The subjects consisted of nine male cyclists competing either in time-trials or triathlon events; seven of them were competing at the national or international level. A incremental laboratory cycling test was used to determine $\dot{W}_{PEAK}$, while subjects completed both a 20 min. and 90 min. cycling time-trial to ascertain $\dot{W}_{VT}$. Of the amount of variance in average power output during the 90 minute time-trial $\dot{W}_{PEAK}$ was found to explain fully 83%. Such variance was to be expected, given the homogeneous training background of the subject population.

Peak power output has been correlated with average power output during a one hour maximal laboratory test identical to that of Coyle et al. (1991). Bishop et al. (1998) found a correlation, in a one-hour laboratory test, between $\dot{W}_{PEAK}$ and $\dot{W}_{VT}$ ($r = 0.81$). The researchers suggested that the relationship between $\dot{W}_{PEAK}$ and the $\dot{W}_{VT}$ was similar to that between $\dot{V}O_{2MAX}$ and $\dot{V}O_{2LACTATE}$.

Effects of Position on Power Output

The relationship between power output and cycling position has been explored in several studies (Heil, Wilcox, & Quinn, 1995; Heil et al., 1997; Price & Boone, 1997; Too, 1991, 1994). Given the relationship between power output and performance discussed previously, any change in the power producing capabilities of a cyclist will have a direct impact on performance.

Too (1991) explored the relationship between seat tube angle (STA) and anaerobic power in cycling. Fourteen males were tested through a range of STAs consisting of 65˚, 40˚, 15˚, and -10˚. Each subject completed a Wingate test at one of the STAs during four separate laboratory visits. The results of the study suggest a curvilinear relationship between hip angle (HA) and resultant power production. Anaerobic peak power output ($\dot{W}_{PP}$) was maximized at a STA of 15˚ and a corresponding HA of 75.5˚. Increasing or decreasing the HA relative to a fixed STA of 15˚ resulted in a corresponding reduction in anaerobic $\dot{W}_{PP}$. Too's findings suggest that there is a HA at which power production is maximized. Consequently, increases or decreases in this HA result in reduced power production capability. However, Too's findings were limited in that the cyclists of his subject population were untrained: differences in power production corresponding to slight adjustments in HA may be more defined and less variable in a population of trained cyclists than in a population of untrained cyclists. In addition, Too tested subjects throughout a very large range of STAs. With the exception of 65˚ STA, the STAs used are considered illegal for use by UCI (Union Cycliste Internationale) standards, competitive cycling's governing body of sanctioned events.

Heil et al. (1995) evaluated the relationship between change in STA and cardiorespiratory measures during submaximal cycling. During the initial testing session, 25 competitive cyclists completed a $\dot{V}O_{2MAX}$ test in their preferred position (P_0). Cyclists were then tested for ten minutes in four different STAs (69°, 76°, 83°, and 90°) at a fixed power output corresponding to 73% of their $\dot{V}O_{2MAX}$. The researchers found that $\dot{V}O_{2SUB}$, heart rate, and the rate of perceived exertion (RPE) of the cyclists were minimized at both the 83° and 90° STAs and maximized at the STA of 69°, which coincided with the smallest HA of the positions tested. Heil et al. suggested that the variation in cardiorespiratory responses was due to the manipulation of STA, resulting in both a change in HA measurements and the length of the working muscles. Variation of the working muscle length may decrease efficiency, thus increasing energy demand to maintain power production.

Heil et al. (1997) examined the effect of both STA and TA variation on $\dot{V}O_{2SUB}$ and heart rate. Three STAs were used (70°, 80°, and 90°) in combination with three separate TAs (10°, 20°, and 30°), resulting in a total of nine different positions. Heil et al. found that both $\dot{V}O_{2SUB}$ and heart rate were minimized at a cyclist's P_0. As HA increased or decreased from P_0, both $\dot{V}O_{2SUB}$ and heart rate increased. The increase in $\dot{V}O_{2SUB}$ and heart rate resulting from an altered HA suggested a decrease in the cyclist's power producing capabilities, resulting in either increased energy demand to maintain $\dot{W}_{VT}$ or decreased $\dot{W}_{PEAK}$. Heil suggested that the increases in $\dot{V}O_{2SUB}$ and heart rate may be due to an increased load on the shoulder musculature through the use of aerobars and changes in the TA of the cyclists.

The influence of TA and STA on $\dot{W}_{PEAK}$ and $\dot{V}O_{2MAX}$ was explored by Welbergen and Clijsen (1990). Six male subjects were tested at two STAs and in two TA conditions, resulting in four different positions. The STAs were comparable to 1) the traditional cycling position (79° angle) labeled as "Sitting" and 2) the recumbent cycling position (30° angle) labeled as "Recumbent." The TAs used for the "Sitting" position were defined as 1) upright (near vertical) and 2) racing (near horizontal). The TAs used in the "Recumbent" position were 1) supine and 2) prone. Incremental laboratory cycling tests were performed in each of the positions to measure $\dot{W}_{PEAK}$. Welbergen and Clijsen's research showed that cyclists' $\dot{W}_{PEAK}$ was maximized in the "Sitting" position with a TA near vertical, while it was minimized in the "Recumbent" position with a prone TA. The various positions tested had no effect on $\dot{V}O_{2MAX}$. However, each of the positions produced in this study resulted in a different $\dot{W}_{PEAK}$ value, reinforcing the idea that $\dot{W}_{PEAK}$ is maximized at a certain HA. Unfortunately, Welbergen and Clijsen did not precisely report TA or HA measurements. In addition, the varied training backgrounds of the cyclists, triathletes, and recumbent cyclists tested resulted in a heterogeneous subject population. The lack of specific angle measurements, the heterogeneous nature of the subjects, and the small testing population thus limit the use of these research results.

Gnehm, Reichenbach, Altpeter, Widmer, and Hoppeler (1997) investigated the metabolic consequences of riding in an aerodynamic time-trial position. Fourteen elite male cyclists were tested on two separate occasions. The initial laboratory visit measured $\dot{V}O_{2MAX}$ using each subject's own racing bicycle. During the second laboratory visit, each subject was tested in three different positions at a workload equivalent to 70% of

$\dot{V}O_{2MAX}$. The three positions employed were 1) an upright position (hands positioned on the top of the handlebars), 2) a drop bar position (hands positioned on the drops of the handlebars), and 3) an aerodynamic cycling position (forearms positioned on aerodynamic time-trial handlebars). Gnehm et al. found that $\dot{V}O_{2SUB}$ increased by 1.5% when subjects changed from the upright position to the drop bar position, and by a further 1.5% when they switched to the aerodynamic position. Gnehm et al. suggested that the increases in $\dot{V}O_{2SUB}$ may have been caused by 1) the increased use of upper body musculature as TA was decreased and 2) increased hip flexion (decreased HA), resulting in changes in the force-velocity and force-length curves for leg musculature. A change in the muscle's operating position on the force-velocity and force-length curves should result in a decreased capacity to produce power, increasing the energy expenditure (i.e., $\dot{V}O_{2SUB}$) needed to maintain the workload. Unfortunately, Gnehm et al. did not measure HA; consequently, the amount of power loss resulting from a change in HA cannot be calculated. They also neglected to control for an increased load on the upper body musculature which may have led to increases in $\dot{V}O_{2SUB}$.

Richardson and Johnson (1994) investigated the effect of both normal and aerodynamic handlebars on the $\dot{V}O_{2SUB}$ of cyclists. They tested eleven elite male cyclists four times each, twice in each position. Each trial consisted of a 4 km time-trial on a flat course. Subjects' speed was kept constant at 40 km/hr by a pacing motor scooter. Expired gases were collected during the last 45 seconds of each trial using a 1501 Douglas bag attached to the motor scooter. Time-trials in the normal position allowed the cyclists to choose their own position using a set of normal drop handlebars. The aerodynamic position was defined as forearms positioned on aerobars attached to the cyclist's normal handlebars. Significantly, HA was not controlled during any of the trials. The authors found that the aerodynamic position resulted in a lower $\dot{V}O_{2SUB}$ than the normal position and suggested that a cyclist's position was more effective with the addition of aerodynamics handlebars. However, there are three important points to consider in the interpretation of these findings. First, in the normal position, "…subjects were allowed to adopt what they considered to be their most suitable position. The majority chose the tucked position…" (p. 860). A tucked position involves increased flexion of the elbow and hip joints, as well as increased load in the upper body musculature. This additional upper body load could indicate that the decreased $\dot{V}O_{2SUB}$ was due to the body's increased skeletal support in the aerodynamic handlebars by allowing cyclists to rest on their elbows. Second, the aerodynamic handlebars decreased the cyclists' frontal area, thereby decreasing aerodynamic drag. Where speed is held constant, decreases in aerodynamic drag will result in decreased energy demand, thereby decreasing $\dot{V}O_{2SUB}$. Lastly, HA was neither controlled nor measured in either position. It is possible that some of the cyclists had a smaller HA in the normal position than in the aerodynamic position. Consequently, the aerodynamic position may have represented a HA closer to a cyclist's $P_{0,}$ resulting in increased power producing ability and a lower $\dot{V}O_{2SUB}$ at a fixed speed.

By contrast, a study by Origenes, Blank, and Schoene (1993) indicated that aerodynamic positions did not increase either $\dot{V}O_{2MAX}$ or heart rate. The authors studied the respective effects of upright and aerodynamic cycling positions on $\dot{V}O_{2MAX}$, maximal heart rate and $\dot{W}_{PEAK}$ of 10 moderately trained males. The subjects were four triathletes, two high-altitude climbers, and four untrained, but recreationally active, individuals. The two positions employed were 1) the upright position (hands positioned on the brake-lever hoods, arms extended, and elbows slightly bent) and 2) the aerodynamic position (forearms positioned on the top of the aero-handlebars). Each subject completed a $\dot{V}O_{2MAX}$ test to exhaustion in both positions. No significant differences between the two positions were found with respect to $\dot{V}O_{2MAX}$, maximal heart rate, or $\dot{W}_{PEAK}$. The heterogeneous training background of the subject population implies that they were not trained in specific HAs. Accordingly, no differences were to be expected between the positions tested.

The effects of a cyclist's position on metabolic output was investigated by Grappe, Candau, Busso, and Rouillon (1998). Nine nationally competitive male cyclists were administered a $\dot{V}O_{2MAX}$ test followed by a laboratory testing session during which each rider rode in three positions at a workload equivalent to 70% of their maximum. The positions employed during the laboratory testing were defined as 1) the upright posture (hands positioned on the brake hoods), 2) the dropped posture (hands positioned on the bottom part of the handlebars), and 3) the aerodynamic position (forearms positioned on the top of the aero-handlebars). Grappe et al. found a higher rate of perceived exertion (RPE) and ventilatory response in the dropped posture when compared to the upright posture. Conversely, they found no difference in either ventilatory or metabolic measures between the dropped and aerodynamic posture. The authors suggested that the difference in physiological measures could be explained by the change in hip flexion. However, Grappe et al. did not determine HAs as a variant of a cyclist's P_0. Consequently, one of the experimental positions may have resulted in a HA equivalent to one cyclist's P_0, while the same HA may have been greater or less than another cyclist's P_0. It is possible that more significant differences in physiological measures may have been realized had the HA of each position been controlled using each cyclist's P_0 as a reference point. Consequently, the validity of the data was limited when comparing the positions across the entire subject pool.

Heil (1997) explored the response to increased load on the upper body musculature of a cyclist. Seven competitive cyclists were tested at three different inclines: -5˚, 0˚, and 5˚. The testing ergometer was placed on a treadmill capable of producing the three inclines being tested, and cyclists mounted their machines on it in an aerodynamic cycling position. This was done to measure the effects on a cyclist's upper body musculature of shifting their weight balance forward while adopting the aerodynamic position. Heil found a strong correlation between heart rate at the -5˚ incline and EMG from the anterior deltoid and long head of the triceps brachii. Heil suggested that increased use of upper body musculature could result in increased physiological demand. It follows that additional research using positions requiring an increased utilization of upper body musculature must address this subsequent increase in energy demand.

Muscle Specificity

Competitive cyclists train between 600 and 1200 hours per year. Much of the training is done in a cyclist's preferred position (P_0), or the position that each cyclist finds most comfortable. This P_0 appears to be initially self-chosen, but may be changed as experience increases. The chosen training position will affect the muscles of the lower limbs, hip extensors, and lower back muscles, resulting in certain muscle lengths where power production is maximized.

Cavanagh and Williams (1982) investigated the relationship between stride length and $\dot{V}O_{2SUB}$ in 10 trained male runners. They hypothesized that manipulating a runner's stride length would have important consequences on their economy. Oxygen consumption was measured while they ran at their preferred, or self-chosen, stride length, and respectively at ±6.7%, ±13.4%, and ±20% of their self-selected stride length. Cavanagh and Williams found that each runner displayed a certain stride length at which $\dot{V}O_{2SUB}$ was minimized, and took this to be their optimal. In addition, they found that each subject's self-chosen stride length produced a $\dot{V}O_{2SUB}$ that averaged a difference no greater than 0.2 $ml \cdot kg^{-1} \cdot min^{-1}$ from their optimal. The authors concluded that trained runners tended to run at a stride length very close to their optimal, and provided two explanations for this observation. The first was that runners chose their preferred stride length through some type of feedback mechanism alerting them to the location of a stride length in relation to their optimal. The second explanation was that runners were able to adapt to certain stride lengths through training. Based on this observation, runners who did not initially choose their most efficient stride length may, through training, adapt effectively to the chosen stride length, thereby making it optimal.

The minimization of $\dot{V}O_{2SUB}$ during submaximal exercise was reviewed by Cavanagh and Kram (1985). The article defined a very important concept of athletic performance, called the optimal phenomenon. An optimal phenomenon was defined as the minimization of energy cost when certain biomechanical variables were manipulated. One example was a cyclist's seat height (SH): there was a SH at which $\dot{V}O_{2SUB}$ was minimized and power output maximized. If this SH was either increased or decreased, $\dot{V}O_{2SUB}$ would be increased and power output decreased. The notion of optimal phenomenon might thus help explain energy expenditure differences between two athletes performing the same task. Cavanagh and Kram suggested that athletes may perform on different points of their optimal phenomena curve, and that some would be able to minimize energy expenditure through self-feedback. Consequently, small adjustments along the optimal phenomena curve would result, at the elite level of athletics, in noticeable changes in performance.

Koh (1995) reviewed evidence of serial sarcomere adaptation as a result of strength training. The author provided evidence that serial sarcomere numbers may adapt to muscle force, in turn leading to changes in muscle force-length properties. Koh hypothesized that if an athlete was trained to produce maximal force at a different joint angle, serial sarcomere length would be optimized at this angle through a training effect. This would result in the muscle producing maximal force at this new joint angle. Koh was able to show, through modeling, that the torque production of the quadriceps varied throughout its range, despite its maximum force producing capacity remaining constant. The author showed that changing the serial sarcomere length-joint angle relation changed the joint angle at which the quadriceps produced maximal force. He concluded by suggesting that serial sarcomere lengths were a constantly changing process used by the body to optimize a muscle's force producing capabilities to match the joint angle at which maximum force was required. Finally, Koh suggested that joint angle specificity of muscles may not be confined to strength training alone, but might apply equally to other modes of training.

Rassier, MacIntosh, and Herzog (1999) reviewed information regarding the reliance of the muscle length on its force production capabilities. They found that individual muscles in the same person functioned at differing points on their force-length relationship. Rassier et al. suggested that the discrepancy in force-length relationship may be the result of the functional demands of the muscle. They proposed that training adaptations took place in the sarcomere number of the working muscles and that muscles would adapt their force-length properties to meet the specific demands provided by training, conclusions that reinforced the observations of Koh (1995).

Herzog, Guimaraes, Anton, and Carter-Erdman (1991) investigated the premise that speed skaters and cyclists may have differences in the moment-length relationship of the rectus femoris when compared to runners. They tested two groups of highly trained athletes, two of which had competed at the international level. The first group of subjects consisted of three cyclists and one speed skater, the second of four runners. The speed skater and cyclists were grouped together due to the similar rectus femoris lengths achieved during their respective sports. The subjects' maximal voluntary isometric knee extensions were tested on three separate occasions. Three knee angles (ranging between 100˚ and 170˚) and nine HAs (between 90˚ and 170˚) were tested in random combinations during each testing session. Significant differences were found in the moment-length relations of the rectus femoris between the two groups. Cyclists tended to have stronger contractile forces at shorter lengths, while runners were stronger at longer muscle lengths. Herzog et al. suggested that skeletal muscles had the capability to adapt to such functional demands as they were recurrently exposed to. The authors provided evidence that high level athletes may be trained to work most efficiently at certain joint angles and muscle lengths.

Optimal Time-Trial Position

Klippel and Heil (2002) presented an abstract at the 2002 National ACSM Conference merging many of the concepts discussed, creating a mathematical simulation that predicted a cyclist's optimal time trial position. Optimal position was defined as the combination of STA and TA that minimized power demand while maintaining maximal power supply. According to the authors, all that was required to determine a cyclist's optimal time trial position were the STA and TA measurements in their P_0, their body mass (M_B), and their sustainable power output at ventilatory threshold ($\dot{W}_{VT}$) while cycling in their P_0.

The algorithm initially determined the power supply of the relationship. The first step in this process was to use an equation based upon the data collected by Heil et al. (1997) to calculate a cyclist's HA in their P_0:

$$HA = 1.8414 \times STA + 0.8299 \times TA - 91.0208 \qquad (2)$$

This equation used the STA and TA measurements of a cyclist's P_0 to calculate the corresponding mean hip angle (HA) of the position. Next, in order to generate a 2×2 array of HAs for all possible Union Cycliste Internationale (UCI) legal combinations of STA and TA (Table 1), the following equation was used (Table 2):

$$\Delta \mathrm{HA} = [(\mathrm{HA\ from\ Table\ 1}) - (\mathrm{HA\ in\ } P_0)] \tag{3}$$

ΔHA is the difference, in degrees, between the HA corresponding to a cyclist's P_0 and the HAs produced by all UCI legal combinations of STA and TA. This calculation quantified the difference between the HA produced by each position and the HA corresponding to P_0. Then, using an equation reported by Heil et al. (1997), ΔHA was converted into $\Delta\dot{V}O_{2SUB}$:

$$\Delta\dot{V}O_{2SUB} = 0.802 \times \Delta \mathrm{HA} + 0.454 \times \Delta \mathrm{HA}^2 \tag{4}$$

$\Delta\dot{V}O_{2SUB}$ was expressed in units of $\mathrm{ml \cdot min^{-1}}$ (the original equation was in $\mathrm{l \cdot min^{-1}}$) and ΔHA in units of degrees. In that study, Heil had tested combinations of three STAs and three TAs in an attempt to find one that minimized $\dot{V}O_{2SUB}$. While, Heil had not found a particular combination of STA and TA that minimized $\dot{V}O_{2SUB}$, the data indicated that positions resulting in HAs similar to that produced by each cyclist's P_0 did result in lower $\dot{V}O_{2SUB}$ values. Heil had proposed that the HA corresponding to a cyclist's P_0 may produce the lowest $\dot{V}O_{2SUB}$ values. He had also suggested that either increasing or decreasing HA by changing a cyclist's STA or TA would produce increased $\dot{V}O_{2SUB}$ values. The resulting equation used to convert ΔHA into $\Delta\dot{V}O_2$ values was based on data collected from the nine combinations of STA and HA. The HAs produced by these positions had not been systematically centered on, nor had been designed to include, that HA which corresponded to each cyclist's P_0. As a result, Klippel and Heil's algorithm assumed that the HA produced by each cyclist's P_0 was the HA that resulted in the lowest $\dot{V}O_{2SUB}$ values.

To translate a change in $\dot{V}O_{2SUB}$ into a change in power supply, the efficiency of the cyclist must be estimated. Francescato, Girardis, and di Prampero (1995) had defined the relationship between power output ($\dot{W}$) and $\dot{V}O_{2SUB}$ in cyclists, developing an efficiency calculation that derived $\Delta\dot{W}$ from $\Delta\dot{V}O_2$ at fixed pedal cadences between 40 and 100 rpm. Therefore the next step in Klippel and Heil's (2002) algorithm was to calculate delta efficiency (Δη):

$$\Delta\eta = (3.59\mathbf{5}10^{-5}) \times (f_\rho)^2 - 0.003 \times f_\rho + 0.326 \qquad (5)$$

Δη ($\Delta\dot{W}/\Delta\dot{V}O_{2SUB}$; $\Delta\dot{V}O_{2SUB}$ was in units of $ml\cdot min^{-1}$) was the delta efficiency as a function of pedal cadence (f_ρ, in revolutions per minute).

Next, Klippel and Heil's (2002) algorithm further refined the power supply measure. Using a cyclist's $\dot{W}_{VT}$ in P_0 and Δη, $\dot{W}_{VT}$ for each combination of STA and TA could be calculated from the $\Delta\dot{V}O_{2SUB}$ values provided by Equation 3:

(6)

$$\text{Corrected } \dot{W}_{VT} = \dot{W}_{VT}(\text{in } P_0) - (\Delta\dot{V}O_{2SUB} \text{ from Equation 3}) \times (\Delta\dot{W} / \Delta\dot{V}O_2 \text{ from Equation 4})$$

Equation 6 was used to create a third 2×2 array (Table 3) containing $\dot{W}_{VT}$ for each position, or combination, of STA and TA. The information produced by Table 3 represented an estimation of the maximal $\dot{W}_{VT}$ produced in each position at a steady state. To calculate the maximal speed that a cyclist could achieve in a given position, this power supply needed to be compared to the amount of power demand required to overcome aerodynamic resistance in that position.

Aerodynamic resistance is largely determined by a cyclist's frontal area, as previously discussed (Bassett, Kyle, Passfield, Broker, and Burke, 1999; Di Prampero et al., 1979; Olds et al., 1995; Olds, 2001; Whitt, 1971). Therefore, a fourth 2×2 array (Table 4) was created to compute the projected frontal area (A_ρ) of each combination of STA and TA. The A_ρ was calculated using the following formula reported by Heil (2001):

$$A_\rho = 0.00433 \times (STA^{0.172}) \times (TA^{0.096}) \times (M_B{}^{0.762}) + 0.10 \qquad (7)$$

A_ρ is projected frontal area of both cyclist and bicycle (m^2), and M_B is body mass (kg).

Lastly, a 2×2 array (Table 5) was created to provide final ground speed ($\dot{s}$) for the cyclist in each combination of STA and TA. Aerodynamic drag was calculated using:

$$R_D = 0.5 \times \rho \times C_D \times A_\rho \times v^2 \qquad (8)$$

It was assumed that air density (ρ) was constant at a value of 1.2, the coefficient of drag (C_D) was constant at 0.8, and that velocity (v) = average ground speed ($\dot{s}$) in $m \cdot s^{-1}$. Maximal ground speed ($\dot{s}$) was solved iteratively by determining the point at which power supply, $\dot{W}_{VT}$, was equivalent to power demand, R_D:

$$\dot{s} = (\dot{W}_{VT} / R_D) = \dot{W}_{VT} / (0.48 \times A_\rho \times v^2) \qquad (9)$$

Since velocity was considered equal to ground speed, it was assumed there was no direction change or wind other than that produced through the movement of the cyclist. Given that flat land time-trial cycling was being modeled, these assumptions were justified. Equation 9 was iteratively solved for $\dot{s}$ using a program written in Visual Basic. The STA and TA combination resulting in the highest $\dot{s}$ represented the optimal time-trial position. This optimal position corresponded to the most effective approach to minimizing frontal area and aerodynamic drag, while simultaneously maintaining a $\dot{W}_{VT}$ equivalent to that achievable in the cyclist's P_0. Since the goal of a time-trial cyclist is to maintain the highest average speed possible, this position maximized their performance capabilities.

An assumption of Klippel and Heil's (2002) algorithm was that the HA corresponding to P_0 was equivalent to the HA that maximized power output. Since Heil at al. (1997) had not actually tested cyclists in their P_0, or systematically manipulate their

HA around that produced by P_0, it may be assumed that the relationship defined by Equation 4 was correct.

The relationship between $\dot{V}O_{2SUB}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) and P_0 has not been systematically explored. While the previous research had suggested that a relationship existed between HA and both power output and $\dot{V}O_2$, the extent to which a cyclist's P_0 was involved was unknown. Alterations in muscle architecture, resulting from training adaptations, may effect this relationship. In order to find the optimal balance between aerodynamic resistance and $\dot{W}_{VT}$, it was necessary to define this relationship accurately.

Table 1. Mean hip angles (HA, degrees) resulting from combinations of seat tube and trunk angle according to Equation 2.

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	39	40	40	41	42	43	44	45	45	46	47	48	49	49	50	51	52	53	54	54	55	56	57	58	59	59	60	61	62	63
71	41	41	42	43	44	45	46	46	47	48	49	50	51	51	52	53	54	55	55	56	57	58	59	60	60	61	62	63	64	65
72	42	43	44	45	46	47	47	48	49	50	51	52	52	53	54	55	56	56	57	58	59	60	61	61	62	63	64	65	66	66
73	44	45	46	47	48	48	49	50	51	52	53	53	54	55	56	57	58	58	59	60	61	62	62	63	64	65	66	67	67	68
74	46	47	48	49	49	50	51	52	53	54	54	55	56	57	58	59	59	60	61	62	63	64	64	65	66	67	68	68	69	70
75	48	49	50	50	51	52	53	54	55	55	56	57	58	59	60	60	61	62	63	64	65	65	66	67	68	69	69	70	71	72
76	50	51	51	52	53	54	55	56	56	57	58	59	60	61	61	62	63	64	65	66	66	67	68	69	70	71	71	72	73	74
77	52	52	53	54	55	56	57	57	58	59	60	61	62	62	63	64	65	66	67	67	68	69	70	71	72	72	73	74	75	76
78	53	54	55	56	57	58	58	59	60	61	62	63	63	64	65	66	67	68	68	69	70	71	72	73	73	74	75	76	77	78
79	55	56	57	58	59	59	60	61	62	63	64	64	65	66	67	68	69	69	70	71	72	73	74	74	75	76	77	78	79	79
80	57	58	59	60	60	61	62	63	64	65	65	66	67	68	69	70	70	71	72	73	74	75	75	76	77	78	79	80	80	81
81	59	60	61	61	62	63	64	65	66	66	67	68	69	70	71	71	72	73	74	75	76	76	77	78	79	80	81	81	82	83
82	61	62	62	63	64	65	66	67	67	68	69	70	71	72	72	73	74	75	76	77	77	78	79	80	81	82	82	83	84	85
83	63	63	64	65	66	67	68	68	69	70	71	72	73	73	74	75	76	77	78	78	79	80	81	82	83	83	84	85	86	87
84	64	65	66	67	68	69	69	70	71	72	73	74	74	75	76	77	78	79	79	80	81	82	83	84	84	85	86	87	88	89
85	66	67	68	69	70	70	71	72	73	74	75	75	76	77	78	79	80	80	81	82	83	84	85	85	86	87	88	89	90	90
86	68	69	70	71	71	72	73	74	75	76	76	77	78	79	80	81	81	82	83	84	85	86	86	87	88	89	90	91	91	92
87	70	71	72	73	73	74	75	76	77	77	78	79	80	81	82	82	83	84	85	86	87	87	88	89	90	91	92	92	93	94
88	72	73	74	74	75	76	77	78	78	79	80	81	82	83	83	84	85	86	87	88	88	89	90	91	92	93	93	94	95	96
89	74	75	75	76	77	78	79	80	80	81	82	83	84	84	85	86	87	88	89	89	90	91	92	93	94	94	95	96	97	98
90	76	76	77	78	79	80	81	81	82	83	84	85	85	86	87	88	89	90	90	91	92	93	94	95	95	96	97	98	99	100

Table 2. Example change in mean hip angle (HA, degrees) for a preferred position (P_0) corresponding to a seat tube angle (STA, degrees) of 73° and trunk angle (TA, degrees) of 20°. Areas highlighted are positions that elicit a HA within 1° of P_0.

Trunk Angle (degrees)

Seat Tube Angle (degrees)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	-21	-20	-20	-19	-18	-17	-16	-15	-15	-14	-13	-12	-11	-11	-10	-9	-8	-7	-6	-6	-5	-4	-3	-2	-1	-1	0	1	2	3
71	-19	-19	-18	-17	-16	-15	-14	-14	-13	-12	-11	-10	-9	-9	-8	-7	-6	-5	-5	-4	-3	-2	-1	0	0	1	2	3	4	5
72	-18	-17	-16	-15	-14	-13	-13	-12	-11	-10	-9	-8	-8	-7	-6	-5	-4	-4	-3	-2	-1	0	1	1	2	3	4	5	6	6
73	-16	-15	-14	-13	-12	-12	-11	-10	-9	-8	-7	-7	-6	-5	-4	-3	-2	-2	-1	0	1	2	2	3	4	5	6	7	7	8
74	-14	-13	-12	-11	-11	-10	-9	-8	-7	-6	-6	-5	-4	-3	-2	-1	-1	0	1	2	3	4	4	5	6	7	8	8	9	10
75	-12	-11	-10	-10	-9	-8	-7	-6	-5	-5	-4	-3	-2	-1	0	0	1	2	3	4	5	5	6	7	8	9	9	10	11	12
76	-10	-9	-9	-8	-7	-6	-5	-4	-4	-3	-2	-1	0	1	1	2	3	4	5	6	6	7	8	9	10	11	11	12	13	14
77	-8	-8	-7	-6	-5	-4	-3	-3	-2	-1	0	1	2	2	3	4	5	6	7	7	8	9	10	11	12	12	13	14	15	16
78	-7	-6	-5	-4	-3	-2	-2	-1	0	1	2	3	3	4	5	6	7	8	8	9	10	11	12	13	13	14	15	16	17	18
79	-5	-4	-3	-2	-1	-1	0	1	2	3	4	4	5	6	7	8	9	9	10	11	12	13	14	14	15	16	17	18	19	19
80	-3	-2	-1	0	0	1	2	3	4	5	5	6	7	8	9	10	10	11	12	13	14	15	15	16	17	18	19	20	20	21
81	-1	0	1	1	2	3	4	5	6	6	7	8	9	10	11	11	12	13	14	15	16	16	17	18	19	20	21	21	22	23
82	1	2	2	3	4	5	6	7	7	8	9	10	11	12	12	13	14	15	16	17	17	18	19	20	21	22	22	23	24	25
83	3	3	4	5	6	7	8	8	9	10	11	12	13	13	14	15	16	17	18	18	19	20	21	22	23	23	24	25	26	27
84	4	5	6	7	8	9	9	10	11	12	13	14	14	15	16	17	18	19	19	20	21	22	23	24	24	25	26	27	28	29
85	6	7	8	9	10	10	11	12	13	14	15	15	16	17	18	19	20	20	21	22	23	24	25	25	26	27	28	29	30	30
86	8	9	10	11	11	12	13	14	15	16	16	17	18	19	20	21	21	22	23	24	25	26	26	27	28	29	30	31	31	32
87	10	11	12	13	13	14	15	16	17	17	18	19	20	21	22	22	23	24	25	26	27	27	28	29	30	31	32	32	33	34
88	12	13	14	14	15	16	17	18	18	19	20	21	22	23	23	24	25	26	27	28	28	29	30	31	32	33	33	34	35	36
89	14	15	15	16	17	18	19	20	20	21	22	23	24	24	25	26	27	28	29	29	30	31	32	33	34	34	35	36	37	38
90	16	16	17	18	19	20	21	21	22	23	24	25	25	26	27	28	29	30	30	31	32	33	34	35	35	36	37	38	39	40

Table 3. Example sustainable power output (W_{SUS}, watts) for a preferred position (P_0) corresponding to a seat tube angle (STA, degrees) of 73° and trunk angle (TA, degrees) of 20°, and body mass (M_B, kg) of 70kg. Areas highlighted are positions that elicit a W_{SUS} within one watt of P_0.

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	378	384	389	395	400	405	409	414	418	421	425	429	432	435	437	440	442	444	446	447	448	449	450	450	451	451	451	450	449	448
71	390	396	401	406	410	414	418	422	426	429	432	435	438	440	442	444	446	447	448	449	450	451	451	451	450	450	449	448	447	445
72	402	407	411	415	419	423	427	430	433	436	438	441	443	445	446	448	449	450	450	451	451	451	450	450	449	448	447	445	443	441
73	412	416	420	424	427	431	434	436	439	441	443	445	447	448	449	450	450	451	451	451	450	450	449	448	446	445	443	441	439	436
74	421	425	428	431	434	437	439	442	444	445	447	448	449	450	450	451	451	451	450	449	449	447	446	444	442	440	438	435	433	430
75	429	432	435	437	440	442	444	446	447	448	449	450	450	451	451	450	450	449	448	447	446	444	442	440	437	435	432	429	425	422
76	435	438	440	443	444	446	447	449	449	450	451	451	451	450	450	449	448	447	445	444	442	439	437	434	431	428	425	421	417	413
77	441	443	445	446	448	449	450	450	451	451	451	450	450	449	448	447	445	443	441	439	436	434	431	427	424	420	416	412	408	403
78	445	447	448	449	450	450	451	451	451	450	450	449	448	446	445	443	441	438	436	433	430	427	423	419	415	411	407	402	397	392
79	448	449	450	450	451	451	451	450	449	448	447	446	444	442	440	438	435	432	429	426	422	418	414	410	406	401	396	390	385	379
80	450	451	451	451	450	450	449	448	447	446	444	442	440	437	435	432	429	425	421	418	413	409	405	400	395	389	384	378	372	366
81	451	451	450	450	449	448	447	445	443	441	439	437	434	431	428	424	421	417	413	408	403	399	393	388	382	377	371	364	358	351
82	450	450	449	448	446	445	443	441	439	436	433	430	427	424	420	416	412	407	402	397	392	387	381	375	369	363	356	349	342	335
83	449	447	446	444	443	440	438	436	433	430	426	423	419	415	411	406	401	396	391	386	380	374	368	361	355	348	341	333	326	318
84	446	444	442	440	438	435	432	429	426	422	418	414	410	405	400	395	390	384	379	373	366	360	353	346	339	332	324	316	308	299
85	442	439	437	434	431	428	425	421	417	413	409	404	399	394	389	383	377	371	365	358	352	345	337	330	322	314	306	297	289	280
86	436	434	431	427	424	420	416	412	408	403	398	393	388	382	376	370	364	357	350	343	336	328	320	312	304	296	287	278	269	259
87	430	427	423	419	415	411	407	402	397	392	386	381	375	369	362	356	349	341	334	326	319	311	302	294	285	276	266	257	247	237
88	422	419	415	410	406	401	396	391	385	379	373	367	361	354	347	340	332	325	317	309	300	292	283	274	264	255	245	235	225	214
89	414	409	405	400	395	389	384	378	372	366	359	353	346	338	331	323	315	307	298	290	281	272	262	253	243	233	222	212	201	190
90	404	399	394	388	383	377	371	364	358	351	344	337	329	321	313	305	297	288	279	270	260	251	241	230	220	209	198	187	176	164

Table 4. Example frontal area (A_P, m^2) for all combinations of seat tube angle (STA, degrees) and trunk angle (TA, degrees). Areas highlighted are positions that elicit the smallest A_P.

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	0.33	0.34	0.35	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42
71	0.33	0.35	0.36	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42
72	0.33	0.35	0.36	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42
73	0.33	0.35	0.36	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42
74	0.33	0.35	0.36	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42
75	0.33	0.35	0.36	0.36	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42
76	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42
77	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42
78	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
79	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
80	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
81	0.33	0.35	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43
82	0.34	0.35	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43
83	0.34	0.35	0.36	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43
84	0.34	0.35	0.36	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43
85	0.34	0.35	0.36	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43
86	0.34	0.35	0.36	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43
87	0.34	0.35	0.36	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43
88	0.34	0.35	0.36	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43
89	0.34	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43	0.43
90	0.34	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43	0.43

Table 5. Example maximal ground speed (kph) for a preferred position (P_0) corresponding to a seat tube angle (STA, degrees) of 73° and trunk angle (TA, degrees) of 20°, and body mass (M_B, kg) of 70kg. Areas highlighted are positions that elicit the highest maximal ground speed.

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	51.4	50.9	50.6	50.5	50.5	50.5	50.5	50.5	50.5	50.5	50.6	50.6	50.6	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.6	50.6	50.6	50.5	50.5	50.4	50.3	50.3
71	51.9	51.4	51.1	51.0	50.9	50.8	50.8	50.8	50.8	50.8	50.8	50.8	50.9	50.9	50.9	50.8	50.8	50.8	50.8	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.3	50.2	50.1
72	52.4	51.8	51.5	51.3	51.2	51.2	51.1	51.1	51.1	51.0	51.0	51.0	51.0	51.0	51.0	50.9	50.9	50.9	50.8	50.8	50.7	50.7	50.6	50.5	50.4	50.3	50.3	50.1	50.0	49.9
73	52.8	52.2	51.8	51.7	51.5	51.4	51.4	51.3	51.3	51.2	51.2	51.2	51.1	51.1	51.0	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.5	50.4	50.3	50.2	50.1	50.0	49.8	49.7
74	53.2	52.5	52.1	51.9	51.8	51.7	51.6	51.5	51.4	51.4	51.3	51.2	51.2	51.1	51.1	51.0	50.9	50.8	50.8	50.7	50.6	50.5	50.4	50.3	50.1	50.0	49.9	49.7	49.6	49.4
75	53.5	52.8	52.4	52.1	52.0	51.8	51.7	51.6	51.5	51.4	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.7	50.5	50.4	50.3	50.2	50.1	49.9	49.8	49.6	49.4	49.3	49.1
76	53.7	53.0	52.6	52.3	52.1	51.9	51.8	51.7	51.6	51.5	51.4	51.3	51.2	51.1	51.0	50.9	50.8	50.6	50.5	50.4	50.3	50.1	50.0	49.8	49.6	49.5	49.3	49.1	48.9	48.7
77	53.9	53.1	52.7	52.4	52.2	52.0	51.9	51.7	51.6	51.5	51.4	51.2	51.1	51.0	50.9	50.7	50.6	50.5	50.3	50.2	50.0	49.9	49.7	49.5	49.3	49.1	48.9	48.7	48.5	48.3
78	54.0	53.3	52.8	52.5	52.3	52.1	51.9	51.7	51.6	51.4	51.3	51.2	51.0	50.9	50.7	50.6	50.4	50.3	50.1	49.9	49.8	49.6	49.4	49.2	49.0	48.8	48.5	48.3	48.1	47.8
79	54.1	53.3	52.9	52.5	52.3	52.1	51.9	51.7	51.5	51.3	51.2	51.0	50.9	50.7	50.5	50.4	50.2	50.0	49.8	49.6	49.4	49.2	49.0	48.8	48.6	48.3	48.1	47.8	47.6	47.3
80	54.2	53.4	52.9	52.5	52.2	52.0	51.8	51.6	51.4	51.2	51.0	50.8	50.7	50.5	50.3	50.1	49.9	49.7	49.5	49.3	49.1	48.8	48.6	48.3	48.1	47.8	47.6	47.3	47.0	46.7
81	54.2	53.3	52.8	52.5	52.1	51.9	51.6	51.4	51.2	51.0	50.8	50.6	50.4	50.2	50.0	49.8	49.6	49.3	49.1	48.9	48.6	48.4	48.1	47.8	47.6	47.3	47.0	46.7	46.4	46.0
82	54.1	53.3	52.7	52.3	52.0	51.7	51.5	51.2	51.0	50.8	50.6	50.3	50.1	49.9	49.7	49.4	49.2	48.9	48.7	48.4	48.2	47.9	47.6	47.3	47.0	46.7	46.4	46.0	45.6	45.3
83	54.0	53.2	52.6	52.2	51.8	51.6	51.3	51.0	50.7	50.5	50.3	50.0	49.8	49.5	49.3	49.0	48.7	48.5	48.2	47.9	47.6	47.3	47.0	46.7	46.3	46.0	45.6	45.3	44.9	44.5
84	53.9	53.0	52.4	52.0	51.6	51.3	51.0	50.7	50.4	50.2	49.9	49.6	49.4	49.1	48.8	48.5	48.3	48.0	47.6	47.3	47.0	46.7	46.4	46.0	45.6	45.2	44.9	44.4	44.0	43.6
85	53.7	52.8	52.2	51.8	51.4	51.0	50.7	50.4	50.1	49.8	49.5	49.2	48.9	48.6	48.3	48.0	47.7	47.4	47.1	46.7	46.4	46.0	45.6	45.2	44.8	44.4	44.0	43.5	43.1	42.6
86	53.5	52.5	51.9	51.4	51.0	50.7	50.3	50.0	49.7	49.4	49.1	48.7	48.4	48.1	47.8	47.4	47.1	46.7	46.4	46.0	45.6	45.2	44.8	44.4	44.0	43.5	43.0	42.5	42.0	41.5
87	53.2	52.2	51.6	51.1	50.7	50.3	49.9	49.6	49.2	48.9	48.5	48.2	47.9	47.5	47.1	46.8	46.4	46.0	45.6	45.2	44.8	44.4	43.9	43.5	43.0	42.5	42.0	41.4	40.8	40.2
88	52.8	51.9	51.2	50.7	50.2	49.8	49.4	49.1	48.7	48.3	48.0	47.6	47.2	46.9	46.5	46.1	45.7	45.3	44.8	44.4	43.9	43.4	42.9	42.4	41.9	41.4	40.8	40.2	39.5	38.9
89	52.5	51.4	50.8	50.2	49.8	49.3	48.9	48.5	48.1	47.7	47.3	46.9	46.5	46.1	45.7	45.3	44.8	44.4	43.9	43.4	42.9	42.4	41.9	41.3	40.7	40.1	39.5	38.8	38.1	37.3
90	52.0	51.0	50.3	49.7	49.2	48.8	48.3	47.9	47.5	47.1	46.6	46.2	45.8	45.3	44.9	44.4	43.9	43.4	42.9	42.4	41.8	41.3	40.7	40.0	39.4	38.7	38.0	37.2	36.4	35.6

CHAPTER 3

METHODS

Experimental Design

Sixteen volunteer competitive cyclists were recruited from the Montana State University Cycling Team in Bozeman, Montana. Each participant had had a minimum of two years' cycling experience, had been actively training for at least four weeks prior to the study, and had prior experience with time-trialing and racing in aerobars. The specifics of the study were explained to all subjects and, upon confirmation of understanding, each signed a consent form approved by the Human Subjects Committee of Montana State University.

Subjects were instructed to report to the Montana State University Movement Science Laboratory on two separate occasions, each separated by no more than seven days to minimize training effects. Participants were instructed to report to the lab for each testing session following a complete day of rest, a similar sleep pattern the night before, and the consumption of a similar pre-test meal. Subjects were instructed not to consume food within one hour and to refrain from caffeine (and other drugs) during the three hours prior to each testing session.

Procedures

Testing Session 1

The purpose of the first visit was to ascertain the test ergometer geometry required to elicit the experimental positions desired. In addition, both maximal oxygen consumption ($\dot{V}O_{2MAX}$) in each subject's preferred position (P_0) and the workloads to be used in Testing Session 2 were determined. Subjects reported to the laboratory with their racing clothing and shoes. The following measures were taken from each subject's personal bicycle: 1) seat tube angle (STA), defined as the acute angle (degrees) between the seat tube and a horizontal line, 2) seat height (SH), defined as the distance (cm) between the center of the bottom bracket and the top of the saddle, 3) top tube length, 4) stem angle, 5) stem length, and 6) crank arm length. Subjects were instructed to change into their racing clothing and ride in their P_0 on their personal bicycle mounted onto a Computrainer Pro stationary trainer. During this time researchers obtained trunk angle (TA) measurements, defined as the acute angle (degrees) between a horizontal line and another intersecting the hip and shoulder joints. The TA measurement obtained was used with the STA measurement in an equation created by Heil et al. (1997) to determine mean hip angle (HA), defined as the mean acute angle (degrees) between the thigh and torso for one pedal revolution:

$$HA = 1.8414 \times STA + 0.8299 \times TA - 91.0208 \qquad (2)$$

This equation was, in turn, used to estimate each cyclist's mean HA.

The test ergometer was placed on the laboratory treadmill. Following this, subjects were transferred to the ergometer. Using the recorded dimensional measures, the geometry of the test ergometer was set to each subject's P_0. Subjects were then instructed to warm-up for 15 minutes. Upon completion of warm-up, each subject was set up for metabolic testing. Subjects were tested using a protocol based on power output created and validated at the Montana State University Movement Science Lab (Heil, Murphy, Mattingly, and Higginson, 2001). This protocol consists of a scaling derived system for determining workload at each stage based on the subject's body mass (M_B). The Computrainer resistance unit was used to control power output changes between stages. Subjects were urged to continue with the test for as long as possible. Attainment of one or more of the following criteria was used to determine that $\dot{V}O_{2MAX}$ was successfully reached: 1) a heart rate within 10 bpm of participant's age-predicted maximum heart rate, 2) failure of participant's heart rate to increase despite an increase in power output, 3) leveling of participant's oxygen consumption ($\dot{V}O_2$) despite an increase in power output, and 4) achieving a respiratory exchange ratio (RER) of 1.10 or greater. Testing was immediately discontinued if subject signaled that they could no longer continue.

The information collected during this testing session provided a reference relationship between power output and oxygen consumption in each subject's P_0. Each subject's ventilatory threshold (VT) was determined using a "combined method" outlined by Gaskill, Ruby, Walker, Sanchez, Serfass, et al. (2001). The "combined method" required that two researchers, independently and randomly, analyze each subject's collected test data. Both researchers used the ventilatory equivalent, excess carbon dioxide, and the modified V-slope methods to determine each subject's VT. Following this determination of VT, the researchers' individual results were compared. If the two calculated VTs were within 3% of each other it was considered a valid measurement. The power output at each subject's ventilatory threshold ($\dot{W}_{VT}$) was recorded and used to determine the workload for the second testing session. If a difference of greater than 3%

was determined between the two calculated VTs, the calculations were reevaluated. If any changes were made, results were compared again. In situations that the 3% discrepancy could not be resolved, the subject was either re-tested, or did not continue with the study.

Testing Session 2

The purpose of the test subject's second visit was to collect submaximal physiological measures and film clips in each of five experimental positions determined using measurements collected during the first testing session. The experimental positions consisted of 1) a HA corresponding to each cyclist's P_0, 2) a HA corresponding to –5º of that corresponding to their P_0 (P_{-5}), 3) a HA corresponding to +5º of that corresponding to their P_0 (P_{+5}), 4) a HA corresponding to –10º of that corresponding to their P_0 (P_{-10}), and 5) a HA corresponding to +10º of that corresponding to their P_0 (P_{+10}). The order of the positions was counterbalanced to control any order effect that might occur.

Each of the five experimental positions was determined using Table 1 as a reference. Table 1 contains the HAs produced by all UCI legal combinations of STA and TA calculated from Equation 2.

A treadmill was used to control the grade of the test ergometer and TA relative to the horizontal. However, since any change in treadmill grade would have altered both the position of the saddle relative to the bottom bracket and the pedaling dynamics of the cyclist being tested, identical angle changes (degrees) were made in both TA and STA to produce the changes in HA necessary to preserve consistency in the pedaling dynamics. In general, two degrees of change in both the TA and STA were required to produce a change of five degrees in HA. An example of this procedure was a cyclist whose P_0 produced a hip angle of 60º, corresponding to a STA of 74º and a TA of 18º. A STA of 70º and a TA of 15º was chosen in order for the HA to make the necessary change of -10º. The treadmill grade was set to +3º to control for loading of the upper body musculature caused by the change in TA, resulting in a cumulative effect on STA of only -7º. This contrasted with the -10º that would be experienced had the change been made exclusively in TA and the resultant treadmill control. Another example was a cyclist whose P_0 produced a hip angle of 66º, corresponding to a position consisting of a STA of 75º and a TA of 23º. In order for the HA to make the necessary change of +5º, a STA of 76.5º and a TA of 25º was chosen. The treadmill grade was set to -2º, in order to control for loading of the upper body musculature caused by the change in TA, resulting in the cumulative effect on STA of only +3.5º. This is in contrast to the +5º that would have been produced by a change purely in TA and the resultant treadmill control.

The geometry of the ergometer was adjusted to each subject's first position prior to their arrival at the lab. Following a five-minute warm-up period, the testing itself entailed subjects riding at a power output equal to 85% of $\dot{W}_{VT}$ for a further period of five minutes. The first three minutes were considered an acclimatization phase, allowing cyclists to adopt their natural pedal stroke. Physiological measures were then recorded during the final two minutes of riding, for a 30-sec period of which the subjects were also filmed. Following testing in this first position, subjects were disconnected from the metabolic equipment and allowed to rest while the ergometer geometry was adjusted within five minutes to fit the second position. Testing was repeated for this position, and each of the three subsequent positions, in the same sequence described above. The testing time during this complete session was no longer than one hour, with no more than 30 minutes of actual riding.

Instrumentation

Test Ergometer Specifications

The cycling ergometer used for all testing was a custom built machine, except as noted in what follows. The design allowed adjustment of the ergometer frame geometry via STA, SH, and top-tube length (Figure 4). The ergometer consisted of a Serotta Size-Cycle (Serotta Bicycles, Saratoga Springs, NY), which had been modified by a local bicycle frame builder (Strong Frames, Bozeman, MT) to increase the stability of the unit for maximal testing (Figure 5). The ergometer was equipped with an American Classic seat post (American Classic, Tampa, FL) that allowed for seat height and angle adjustment (Figure 5). The saddle used was a Terry Dragon Fly (Terry Precision Cycling, Macedon, NY) (Figure 5). A LOOK ErgoStem allowed unrestricted adjustment of both stem length and angle (Figure 5) (Veltec Sports Inc., Sand City, CA). The handlebar set-up consisted of Profile AirWing “bull-horn” handlebars with Profile Split-Second aerobars (Profile Design, LLC, Long Beach, CA) attached (Figure 5). The carbon fiber crankset (Murray ‘Tour de Force’ Cycle Technology, Velddrif, South Africa) allowed adjustment of crank length from 160 mm to 190 mm (Figure 5). The ergometer was equipped with a Computrainer resistance unit (RacerMate Inc., Seattle, WA), which allowed adjustment of resistance via the same method described by Heil at al. (2001) as well as measurement of crank revolutions per minute. Subjects used their own pedals, installed prior to each testing session.

Oxygen consumption measures, during both maximal and submaximal testing, were collected using standard indirect calorimetry procedures from a SensorMedics 2900 metabolic cart (SensorMedics Corporation, Yorba Linda, CA, USA). Calibration of the oxygen and carbon dioxide analyzers was accomplished using certified gas mixtures. Ventilation measurements were calibrated using a three-liter (L) syringe (Hans Rudolph, Inc., Kansas City, MO). Oxygen consumption was computed every 20 sec during maximal testing and every 60 sec during submaximal testing. Heart rate measures were recorded using a telemetry-based Polar Vantage Heart Rate Monitor (Polar Electro Inc., Woodbury, NY). Heart rate was recorded at 5 and 60 sec average intervals during $\dot{V}O_{2MAX}$ testing and submaximal testing, respectively.

Resistance was controlled using a Computrainer Pro resistance unit, whose display was attached to the cycling ergometer to provide cadence feedback. The unit itself operated in a manner identical to that described by Heil et al. (2001). The calibration precautions, preparation, and procedures followed were described in the factory user manual and equivalent to those used by Heil et al. On the basis of information acquired through pilot testing, the ergometer was ridden at a power output selected by the subject for a period of no less than 10 min following the initial roll-down calibration. This 10 min interval was determined to be an adequate amount of time needed for both unit warm-up and accurate calibration. After the warm-up, the

Computrainer was reset and another roll-down test was completed, in order to ensure proper calibration.

Next, the subject's personal bicycles were mounted to a Computrainer Pro Stationary Trainer (RacerMate, Inc., Seattle, WA) to measure TA while in P_0. The stationary trainer provided resistance in an identical manner to the resistance unit while allowing the use of each subject's personal bicycle, instead of the ergometer.

A TrackMaster Treadmill (TrackMaster, JAS Fitness Systems, Pensacola, FL) was used to control the grade of the test ergometer and TA relative to horizontal. The use of treadmill grade to control for upper body musculature loading was accomplished in a manner identical to, and based on the findings of, Heil (1997). For example, if preferred TA was 30° and was increased by 10°, the treadmill grade was decreased by 10º to maintain the original TA of 30° relative to horizontal. The aim was to minimize any effect an altered loading of upper body musculature would have on submaximal oxygen consumption ($\dot{V}O_{2SUB}$). Treadmill grade was verified using a gravity inclinometer (Macklanburg-Duncan, Oklahoma City, OK).

Kinematic measurements were made using a Baseline Stainless Goniometer (Country Technology, Inc., Gays Mills, WI), and verified using Peak Motus Version 7.1 Kinematic Analysis Software (Peak Performance Technologies, Inc., Englewood, CO). Filming was done using a JVC TK-C1380 60 Hz Digital Color Video Camera (JVC Americas Corp., Wayne, NJ). Prior to the onset of filming, the Peak Motus software was calibrated by filming for a period of 30 sec a piece of particleboard placed in front of the cycle ergometer with reflective markers attached at pre-measured locations.

Kinematic Analyses

Kinematic analysis of cyclists while on the test ergometer was completed using the film clips recorded during the second testing session, and Peak Motus Version 7.1 Kinematic Analysis Software. Subjects were filmed while riding the ergometer in their P_0 and in the four experimental positions. This film was digitally converted to quantify each subject's 1) TA, 2) HA, and 3) knee angle (KA). Filming for kinematic analysis consisted of a 30 sec, 60 Hz, two-dimensional, saggital film clip in each of the five positions: P_0, P_{-5}, P_{+5}, P_{-10}, and P_{+10}. Reflective markers were placed at the right lateral greater tubercle of the humerus (shoulder joint), the greater trochanter (hip joint), the proximal portion of the lateral condyle of the femur (knee), the lateral malleolus of the fibula (ankle), and the most distal point of the cycling shoe. Five successive pedal revolutions per position were analyzed, selected on the basis of the clarity and "naturalness" of the pedal stroke. All kinematic measurements were taken as an average throughout the selected pedal revolutions.

Statistical Analyses

Analysis was performed to compare each subject's $\dot{V}O_{2SUB}$ in five positions corresponding to HAs equivalent to P_0, $P_{-5,}$ P_{+5}, P_{-10}, and P_{+10}. A repeated measures ANOVA was used to compare measures between positions at a 0.01 alpha level. A

Tukey's multiple comparisons analysis was employed to determine difference between positions, using an error rate of 0.05.

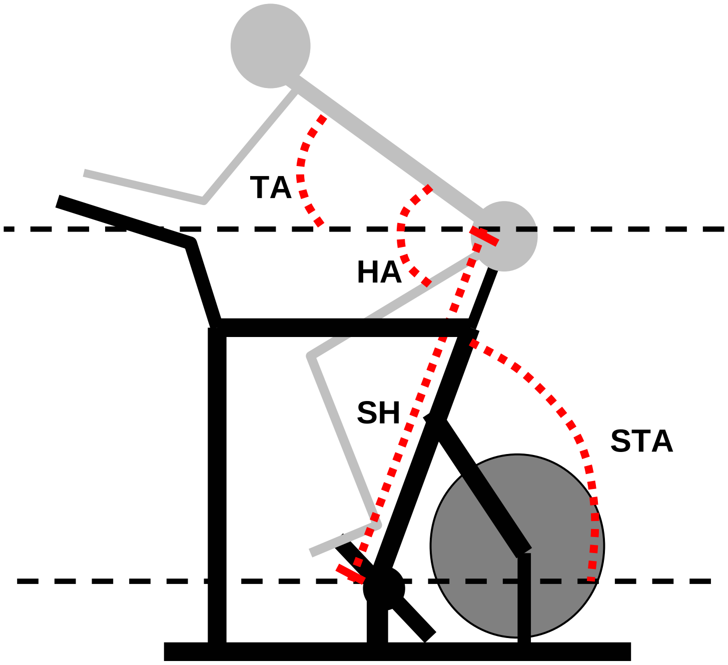

Figure 4. Cycle ergometer used to modify body position. Trunk angle (TA) is defined as the angle between a horizontal line and another one intersecting both the hip and shoulder joints. Hip angle (HA) is defined as the mean angle between the thigh and torso. Seat height (SH) is defined as the distance between the center of the bottom bracket and the top of the saddle. Seat tube angle (STA) is defined as the angle between the seat tube and a horizontal line.

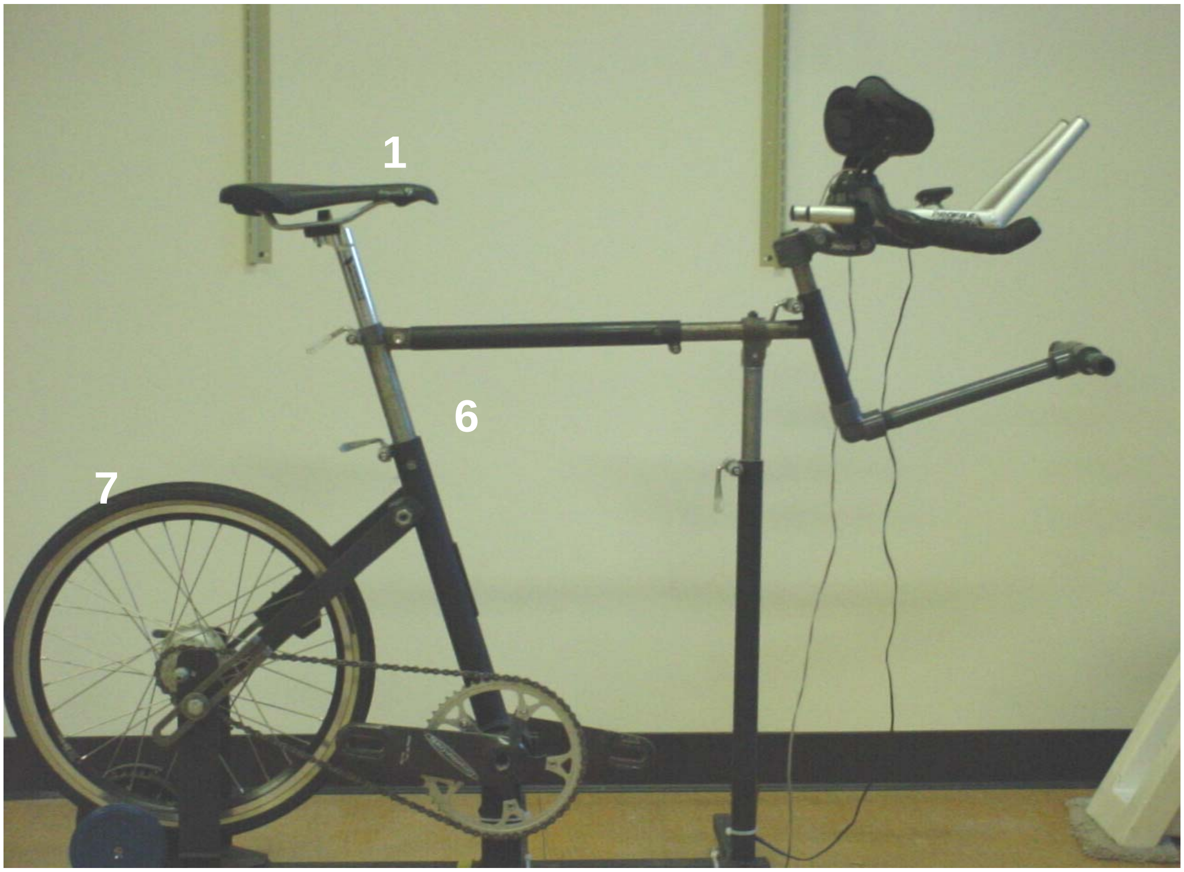

Figure 5. Custom cycling ergometer. (1) Serotta Size-Cycle; (2) American Classic seat post; (3) Terry Dragon Fly saddle; (4) LOOK ErgoStem; (5) Profile AirWing handlebars with Profile Split-Second aerobars; (6) Carbon fiber adjustable crankset; (7) Computrainer resistance unit.

CHAPTER 4

RESULTS

Subjects

Sixteen cyclists from the Montana State University Collegiate Cycling Team were tested, consisting of 15 males and one female. Each participant had minimum of two years of racing experience, as well as experience racing in an aerodynamic time-trial position. Subject characteristics, including maximal oxygen consumption ($\dot{V}O_{2MAX}$) and aerobic peak power output ($\dot{W}_{PEAK}$), are reported in Table 6.

Physiological Data

No significant differences were found when comparing submaximal oxygen consumption ($\dot{V}O_2$), heart rate (HR), or minute ventilation ($\dot{V}_e$) across the five experimental positions (P>0.01, Table 7).

Physiological Data Relative to Preferred Position

The $\dot{V}O_2$, HR, and $\dot{V}_e$ measures at the cyclist's preferred position (P_0) were subtracted from the respective physiological measures at each of the four experimental positions, using the following equations:

$$\Delta\dot{V}O_{2(P)} = (\Delta\dot{V}O_{2SUB}\ @P_i) - (\Delta\dot{V}O_{2SUB}\ @P_0) \tag{10}$$

$$\Delta HR_{(P)} = (\Delta HR\ @P_i) - (\Delta HR\ @P_0) \tag{11}$$

$$\Delta\dot{V}_{e(P)} = (\Delta\dot{V}_e\,@P_i) - (\Delta\dot{V}_e\,@P_0) \tag{12}$$

where P_i represents all five experimental conditions. The result was a delta value centered at each cyclist's P_0. This measurement system presumed each cyclist's P_0 was the position that elicited the lowest physiological measure at a fixed power output. No significant differences were found when comparing $\Delta\dot{V}O_{2(P)}$, $\Delta HR_{(P)}$, and $\Delta\dot{V}_{e(P)}$ across the five experimental positions ($P>0.01$, Table 8).

Although no statistically significant differences were found, a non-significant quadratic relationship was noted between $\Delta\dot{V}O_{2(P)}$, $\Delta HR_{(P)}$, and $\Delta\dot{V}_{e(P)}$ across the five experimental positions (Figures 7, 8, 9).

Minimum Difference Physiological Data

The lowest $\dot{V}O_2$, HR, and $\dot{V}_e$ measures were subtracted, respectively, from the corresponding measures at each of the other four experimental positions. This resulted in difference measures for each of the five experimental positions: $\Delta\dot{V}O_{2(Min)}$, $\Delta HR_{(Min)}$, and $\Delta\dot{V}_{e(Min)}$. The final outcome was a measurement system that did not presume that each cyclist's P_0 was equivalent to the position that elicited the lowest respective physiological measure at a fixed power output (P_{Min}). Therefore, this measurement system was not centerd upon a cyclists' P_0. Since the lowest physiological measures were subtracted from those at each of the remaining experimental positions, the result was a data set made up of entirely positive difference scores. No significant differences were found when comparing $\Delta\dot{V}O_{2(Min)}$, $\Delta HR_{(Min)}$, and $\Delta\dot{V}_{e(Min)}$ across the five experimental positions ($p<0.01$, Table 9).

Kinematic Analysis

A repeated measures ANOVA test was performed on the trunk angle (TA), knee angle (KA), and ankle angle (AA) positioning data in order to verify that no significant differences existed between TA measurements or lower limb kinematics between the five experimental positions. No significant differences were found when comparing TA, KA, and AA across the five experimental positions ($P>0.01$, Table 10).

A repeated measures ANOVA test was performed on the hip angle (HA) measures to confirm that the HA corresponding to each of the five experimental positions was significantly different. Significant differences were found between the HA corresponding to P_{-5} and the HAs corresponding to P_0, P_{+5}, and P_{+10} ($P<0.01$, Table 10). Similarly, significant differences were found between the HA corresponding to P_{-10} and the HAs corresponding to P_0, P_{+5}, and P_{+10}. No significant difference was found between HAs corresponding to P_{-5} and P_{-10}.

Table 6. Subject Characteristics (Means ± SD; n=16).

Age (yrs)	Height (cm)	Body Mass (kg)	$\dot{V}O_{2MAX}$ (l/min)	$\dot{W}_{PEAK}$ (watts)
23.3 ± 3.5	178.3 ± 5.5	73.3 ± 5.9	4.54 ± 0.34	373 ± 40

$\dot{V}O_{2MAX}$ = Maximal Oxygen Consumption, defined as the maximal rate of oxygen a subject can consume during aerobic exercise, measured in absolute terms (L/min); $\dot{W}_{PEAK}$ = Aerobic Peak Power Output, defined as the maximum power output (watts) during an incrementally graded test to exhaustion.

Table 7. Physiological measures across five different cycling positions in collegiate cyclists (Means ± SE (range); n=16).

	P_{-10}	P_{-5}	P_0	P_5	P_{10}	ANOVA P-Value
VO_2 (l/min)	3.3528 ± 0.09	3.3200 ± 0.1087	3.2876 ± 0.1021	3.2834 ± 0.1019	3.2808 ± 0.0958	0.2282
	(2.6305-4.1025)	(2.4435-3.9860)	(2.4495-3.9950)	(2.4460-4.0350)	(2.4620-4.0345)	
HR (bpm)	160.94 ± 2.7969	159.53 ± 3.1280	160.16 ± 3.3338	158.22 ± 2.9283	160.50 ± 3.1748	0.0499
	(139.00-186.00)	(136.00-189.50)	(137.00-191.50)	(134.50-181.00)	(138.50-188.50)	
V_e (l/min)	67.781 ± 3.0256	67.275 ± 3.2463	65.697 ± 2.9041	65.522 ± 3.1355	66.613 ± 3.1776	0.3396
	(51.850-90.900)	(47.600-95.100)	(48.250-91.100)	(49.100-91.950)	(49.350-96.000)	
W_{VT} (watts)			282.13 ± 40.285			
			(160-360)			

P_0 = Preferred Position, defined as the combination of trunk angle (TA) and seat tube angle (STA) in which cyclists spend most of their time training on a bicycle; P_{-10} = Defined as the position resulting in a mean hip angle (HA) ten degrees greater than the HA corresponding to P_0; P_{-5} = Defined as the position resulting in a HA five degrees less than the HA corresponding to P_0; P_5 = Defined as the position resulting in a HA five degrees greater than the HA corresponding to P_0; P_{10} = Defined as the position resulting in a HA ten degrees greater than the HA corresponding to P_0; VO_2 = Oxygen Consumption, the rate of oxygen consumed; HR = Heart Rate; V_e = Minute Ventilation; W_{VT} = Power at Ventilatory Threshold.

Table 8. Difference physiological measures across five different cycling positions in collegiate cyclists based on each cyclist's preferred position (Means ± SE (range); n=16).

	P_{-10}	P_{-5}	P_0	P_5	P_{10}	ANOVA P-Values
$\Delta\dot{V}O_{2(P)}$ (l/min)	0.07 ± 0.05	0.03 ± 0.03	0.00 ± 0.00	-0.01 ± 0.03 l/min	-0.01 ± 0.03 l/min	0.228
	(-0.38-0.45)	(-0.16-0.34)	(0.00-0.00)	(-0.28-0.19)	(-0.18-0.13)	
$\Delta HR_{(P)}$ (bpm)	1 ± 1	-1 ± 1	0 ± 0	-2 ± 1	0 ± 1	0.050
	(-6-12)	(-10-7)	(0-0)	(-11-5)	(-4-5)	
$\Delta\dot{V}_{e(P)}$ (l/min)	2.08 ± 1.24	1.58 ± 0.97	0.00 ± 0.00	-0.18 ± 0.95	0.92 ± 0.92	0.340
	(-5.80-12.90)	(-2.75-13.30)	(0.00-0.00)	(-6.30-6.65)	(-5.10-8.55)	

P_0 = Preferred Position, defined as the combination of trunk angle (TA) and seat tube angle (STA) in which cyclists spend most of their time training on a bicycle; P_{-10} = Defined as the position resulting in a mean hip angle (HA) ten degrees greater than the HA corresponding to P_0; P_{-5} = Defined as the position resulting in a HA five degrees less than the HA corresponding to P_0; P_5 = Defined as the position resulting in a HA five degrees greater than the HA corresponding to P_0; P_{10} = Defined as the position resulting in a HA ten degrees greater than the HA corresponding to P_0; VO_2 = Oxygen Consumption, the rate of oxygen consumed; HR = Heart Rate; V_e = Minute Ventilation.

Table 9. Difference physiological measures across five different cycling positions in collegiate cyclists based on each cyclist's preferred (Means ± SE (range); n=16).

	P_{-10}	P_{-5}	P_0	P_5	P_{10}	ANOVA P-Values
$\Delta\dot{V}O_{2(P)}$ (l/min)	0.16 ± 0.03	0.12 ± 0.03	0.09 ± 0.03	0.09 ± 0.02	0.12 ± 0.04	0.529
	(0.00-0.45)	(0.00-0.37)	(0.00-0.38)	(0.00-0.22)	(0.00-0.68)	
$\Delta HR_{(P)}$ (bpm)	4 ± 1	3 ± 1	3 ± 1	1 ± 1	4 ± 1	0.050
	(1-12)	(0-9)	(0-11)	(0-10)	(0-9)	
$\Delta\dot{V}_{e(P)}$ (l/min)	7.12 ± 1.15	4.16 ± 1.01	2.58 ± 0.48	2.40 ± 0.71	3.49 ± 0.99	0.340
	(0.00-15.45)	(0.00-15.80)	(0.00-6.30)	(0.00-8.05)	(0.00-14.40)	

P_0 = Preferred Position, defined as the combination of trunk angle (TA) and seat tube angle (STA) in which cyclists spend most of their time training on a bicycle; P_{-10} = Defined as the position resulting in a mean hip angle (HA) ten degrees greater than the HA corresponding to P_0; P_{-5} = Defined as the position resulting in a HA five degrees less than the HA corresponding to P_0; P_5 = Defined as the position resulting in a HA five degrees greater than the HA corresponding to P_0; P_{10} = Defined as the position resulting in a HA ten degrees greater than the HA corresponding to P_0; VO_2 = Oxygen Consumption, the rate of oxygen consumed; HR = Heart Rate; V_e = Minute Ventilation.

Table 10. Kinematic angle measurements (degrees) across five different cycling positions in collegiate cyclists (Means ± SE (range) for all subjects; n=16).

	P_{-10}	P_{-5}	P_0	P_5	P_{10}	ANOVA P-Values
Hip Angle (HA)	*53.3 ± 1.17	*56.09 ± 1.23	*59.55 ± 1.23	63.39 ± 1.19	66.87 ± 1.04	0.000
	(44.12-60.88)	(45.63-63.90)	(46.10-65.71)	(53.03-71.13)	(58.40-72.64)	
Trunk Angle (TA)	33.03 ± 1.32	33.32 ± 1.32	34.00 ± 1.30	33.88 ± 1.31	33.86 ± 1.22	0.291
	(18.40-39.12)	(20.99-41.97)	(19.72-41.57)	(20.27-42.07)	(20.65-40.51)	
Knee Angle (KA)	93.06 ± 1.08	92.49 ± 0.85	92.20 ± 0.81	90.67 ± 0.86	90.52 ± 1.11	0.100
	(85.23-99.86)	(87.04-99.32)	(87.02-96.49)	(83.24-96.00)	(83.51-99.54)	
Ankle Angle (AA)	115.65 ± 2.33	116.85 ± 2.47	116.57 ± 2.48	116.07 ± 2.34	116.49 ± 2.07	0.687
	(96.59-132.69)	(97.17-136.97)	(92.11-133.75)	(95.83-132.05)	(99.54-131.64)	

P_0 = Preferred Position, defined as the combination of trunk angle (TA) and seat tube angle (STA) in which cyclists spend most of their time training on a bicycle; P_{-10} = Defined as the position resulting in a mean hip angle (HA) ten degrees greater than the HA corresponding to P_0; P_{-5} = Defined as the position resulting in a HA five degrees less than the HA corresponding to P_0; P_5 = Defined as the position resulting in a HA five degrees greater than the HA corresponding to P_0; P_{10} = Defined as the position resulting in a HA ten degrees greater than the HA corresponding to P_0; HA = Mean Hip Angle, defined as the mean acute angle (degrees) between the thigh and the torso for one pedal revolution; TA = Trunk Angle, defined as the acute angle (degrees) between a horizontal line and another one intersecting the hip and shoulder joints; KA = Knee Angle, defined as the mean acute angle (degrees) between the thigh and lower leg for one pedal revolution; AA = Trunk Angle, defined as the acute angle (degrees) between a horizontal line and another one intersecting the hip and shoulder joints. Significant differences between measurements are indicated by "*".

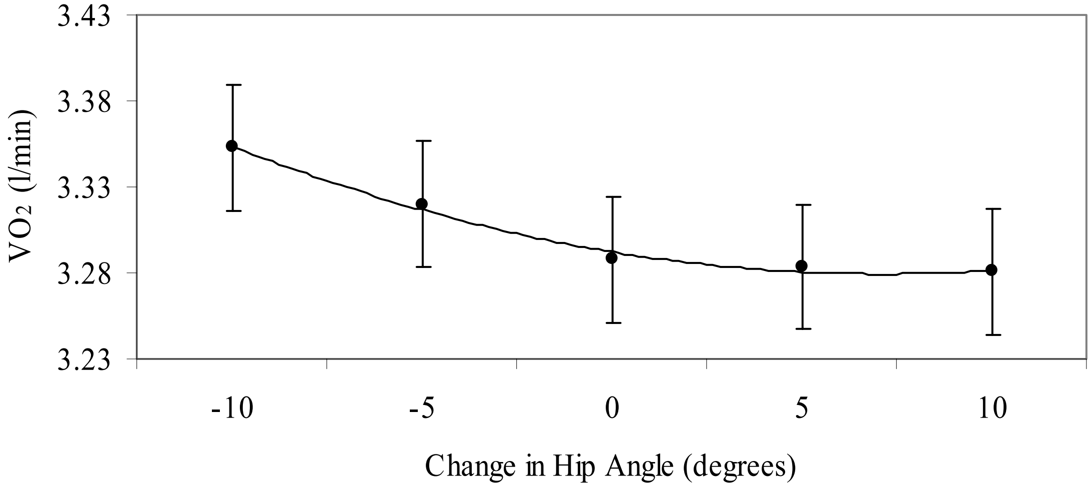

Figure 6. Scatterplot depicts the relationship between mean oxygen consumption (VO_2 and change in hip angle (HA, degrees). Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline: VO_2 (l/min) = 0.0063(ΔHA)2-0.056(ΔHA)+3.4034 (R^2=0.989, SEE=0.0365) .

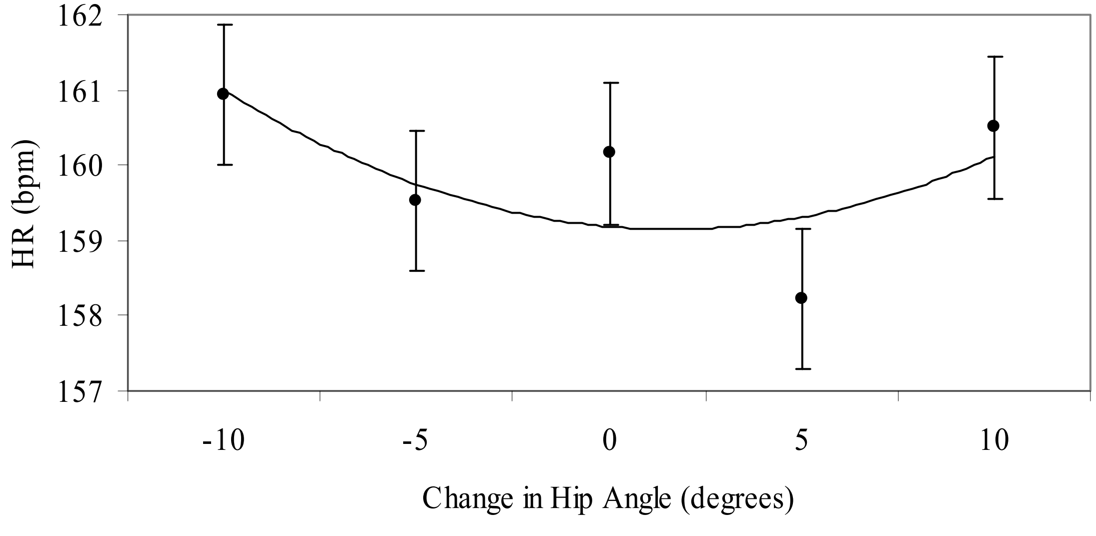

Figure 7. Scatterplot depicts the relationship between mean heart rate (HR) and change in hip angle (HA, degrees). Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline: HR (bpm) = $0.3436(\Delta HA)^2-2.2804(\Delta HA)+162.93$ (R^2=0.4776, SEE=0.9396).

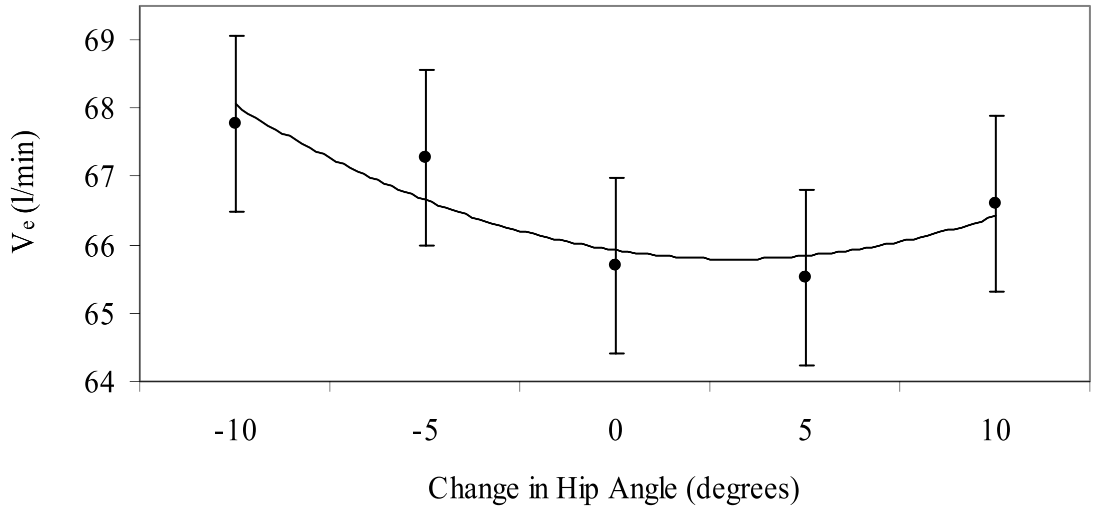

Figure 8. Scatterplot depicts the relationship between mean minute ventilation (V_e) and change in hip angle (HA, degrees). Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline: V_e (l/min) = $0.3284(\Delta HA)^2-2.379(\Delta HA)+70.103$ ($R^2=0.8316$, SEE=1.287).

CHAPTER 5

DISCUSSION

The algorithm developed by Klippel and Heil (2001) used a cyclist's power output at ventilatory threshold ($\dot{W}_{VT}$), and both seat tube angle (STA) and trunk angle (TA) measurements from their preferred position (P_0), to predict a cyclist's optimal time-trial position ($P_{OPTIMAL}$). The proposed algorithm utilized Heil et al.'s (1997) suggestion that a quadratic relationship existed between hip angle (HA), centered at P_0, and power producing capabilities. Heil et al. had proposed that 1) as HA was altered from that of the cyclist's P_0, submaximal oxygen consumption ($\dot{V}O_{2SUB}$) would increase quadratically, and that 2) P_0 was the position that resulted in the lowest oxygen consumption ($\dot{V}O_2$) at a fixed power output. The current study attempted to systematically determine whether the HA corresponding to a cyclist's P_0 minimized $\dot{V}O_{2SUB}$ at a fixed power output.

Five experimental positions were tested at a fixed submaximal power output equivalent to 80% of each subject's $\dot{W}_{VT}$. While no significant differences were found for $\dot{V}O_{2SUB}$ across the five experimental positions, a non-significant quadratic trend with a broad minimum did exist, similar to that proposed by Heil et al. (1997).

In addition, a non-significant quadratic relationship was noted for both mean heart rate and mean minute ventilation ($\dot{V}_e$) across the five experimental positions (Figures 11 and 12) with a broad minimum near P_0. As HA was altered from that corresponding to each cyclist's $P_{0,}$ both HR and V_e increased in a manner similar to that previously discussed for $\dot{V}O_{2SUB}$.

Previous Research

The results of the current study exhibit both similarities with and differences from those reported by Heil et al. (1997). Heil et al. explored the effects of nine different combinations of STA and TA on $\dot{V}O_{2SUB}$ and heart rate. The experimental positions they used resulted in HA manipulations of ±30 degrees, in contrast to the HA manipulations of ±10 degrees used in this study. Even when Heil et al.'s data were confined to ±10 degrees from that corresponding to P_0, $\dot{V}O_{2SUB}$ at a fixed power output increased. In the current study, like that of Heil et al., $\dot{V}O_{2SUB}$ at a fixed power output also increased as HA was decreased from that corresponding to P_0. However, as HA was increased from that corresponding to P_0, $\dot{V}O_{2SUB}$ at a fixed power output either decreased, or remained unchanged (Figure 9). The following equation was reported by Heil et al. to describe the relationship between change in HA and the resultant change in $\dot{V}O_{2SUB}$:

$$\Delta\dot{V}O_2 = 0.000454(\Delta HA)^2 + 0.000802(\Delta HA) \tag{13}$$

By comparison, the following equation was indicated by this study to describe the same relationship:

$$\Delta\dot{V}O_2 = 0.0003(\Delta HA)^2 + 0.0036(\Delta HA) \tag{14}$$

When Heil et al.'s equation is used to quantify the change in $\dot{V}O_{2SUB}$ resulting from a -10° change in HA, a 0.037 L/min increase should result. Correspondingly, a similar increase of 0.066 L/min was found for the -10° change in HA on the basis of the equation reported in this study. When Heil et al.'s equation is used to quantify the change in

$\dot{V}O_{2SUB}$ resulting from a +10º change in HA, a 0.053 L/min increase should result. Conversely, when the equation reported by the current study was used, a decrease of 0.0060 L/min was found for the +10º change in HA. While the quadratic trend between $\dot{V}O_{2SUB}$ and decreases in HA from that corresponding to P_0 appears comparable in the two studies, the results of the present study suggest that increases in HA from that corresponding to P_0 may not result in the increased $\dot{V}O_{2SUB}$ suggested by Heil et al.

Gnehm et al.'s (1997) findings were similar to those indicated by the present study. Gnehm et al. discovered that as a cyclist changed from an upright position (hands positioned on top of the handlebars) to a drop bar position (hands positioned on the drops of the handlebars) $\dot{V}O_{2SUB}$ increased 1.5%. Furthermore, an additional 1.5% increase was found as a cyclist changed from a drop bar position to an aerodynamic position (forearms positioned on aerodynamic time-trial handlebars). When an oxygen consumption of 3 L/min is utilized, each resultant 1.5% increase would be equivalent to 0.045 L/min, an outcome similar to the results of both Heil et al. (1997) and those of the current study. While Gnehm et al. did not report actual HA measurements, it is reasonable to assume that the drop bar position resulted in a HA less than that of the upright position, and that the aerodynamic position resulted in a HA less than those of both the upright and drop bar positions. It is also reasonable to assume the upright position would generally produce a HA similar to most cyclists' P_0. This given, the trend between $\dot{V}O_{2SUB}$ and decreases in HA from that corresponding to P_0 found by Gnehm et al. appears comparable to that same relationship as defined by this study.

Likewise, Grappe et al. (1998) did not report actual measurements for HA, STA, TA, or each subject's P_0, limiting any comparison between its findings and those of the current study. Grappe et al. found an increase in both rate of perceived exertion and ventilatory response in the drop bar position when compared to the upright position. It is reasonable to assume that the drop bar position produces a HA less that that of the upright position, and that the upright position generally produces a HA similar to most cyclists' P_0. While lack of definite HA data does limit the comparison, Grappe et al.'s findings nevertheless seem consistent with those of the current study for decreases in HA from that corresponding to P_0.

Comparison of the current results with Too's research (1991) is also limited, owing to the large range of HAs tested. While Too suggested that a curvilinear relationship existed between HA and power production, only one of the positions tested in Too's study is considered legal for use by the UCI (Union Cycliste Internationale) standards. In comparison, all the positions tested in the current study were within legal UCI standards, and utilized a 20º HA range in contrast to Too's very sizeable, 55.1º range.

Richardson and Johnson (1994) tested 11 elite male cyclists in two positions: 1) a normal position in which each cyclist chose their position using standard drop style handlebars, and 2) an aerodynamic position consisting of forearms positioned on aerobars attached to their standard drop style handlebars. The actual HAs produced by the two experimental conditions were neither reported nor controlled. In addition, all tests were carried out on an outdoor course without control of environmental factors, including the aerodynamic advantage provided by the aerodynamic position. It is reasonable to expect that the reduction in aerodynamic drag provided by Richardson and Johnson's aerodynamic position would have significantly reduced power demand at a fixed speed by reducing frontal area. Consequently, any possible physiological disadvantage produced by the subsequent change in HA would have been masked, thus limiting any comparison between the changes in performance they noted and those of the current study.

Researchers have provided evidence that in less specialized subject populations, less significant trends existed between HA and $\dot{V}O_{2SUB}$ (Heil et al. 1995; Welbergen and Clijsen, 1990; Origenes et al., 1993). An average active population would not have substantial prior training in HAs common to that of competitive cycling and, as a result, no comparable position-specific muscular adaptations. Most endurance sports, such as running and nordic skiing, use HAs that are greater than those common in competitive road cycling. If a competitive road cyclist is cross-trained in a sport that utilizes HAs greater than those common to cycling, the result is an increased efficiency at those larger HAs. It could be argued that if this same cyclist's HA were increased, from that corresponding to their P_0, little, if any, increase in physiological measures would result, owing to this "cross-training" effect. Conversely, any position that resulted in a HA less than the cyclist's P_0 may result in increased physiological measures, such as $\dot{V}O_2$, HR, and $\dot{V}_e$.

Heil et al. (1995) tested 25 cyclists in four STAs (69°, 76°, 83°, and 90°) at a fixed power output corresponding to 73% of each cyclist's $\dot{V}O_{2MAX}$. Cardiorespiratory measures were greatest in the 69° STA condition, or that which produced the smallest

HAs. Conversely, cardiorespiratory measures were minimized in the 83˚ and/or 90˚ STA conditions, or those which produced the largest HAs. Twenty of the subjects were competitive triathletes, a sport that involves intensive "cross-training" in cycling, running, and swimming. Running and swimming involve HA's greater than those used in cycling, therefore it is reasonable to assume that physiological measures were minimized at the conditions producing larger HAs owing to the large proportion of triathletes versus cyclists tested. Researchers have suggested the possibility that adaptations in muscle architecture occur from "cross-training" (Cavanagh and Williams, 1982; Cavanagh and Kram, 1985; Koh, 1995; Rassier et al., 1999; Herzog et al., 1991). In view of the training specific to triathletes, it is logical to expect that these adaptations would improve economy at larger HAs.

Welbergen and Clijsen (1990) also provided evidence of "cross-training" adaptations. Six subjects were tested at four different combinations of STA and TA. The STAs tested consisted of 1) a "sitting" position (comparable to a road position at a 79˚ angle), and 2) a "recumbent" position (comparable to a recumbent bicycle position at a 30˚ angle). The TAs tested were divided into two groups according to the STAs. For the "sitting" STA, TAs tested were 1) an "upright" position (near vertical), and 2) a "racing" position (near horizontal). The TAs tested at the "recumbent" STA were 1) a "supine" position (near vertical), and 2) a "prone" position (near horizontal). The subjects who participated in the study were described as three competitive cyclists/triathletes and three experienced recumbent cyclists. Welbergen and Clijsen found that peak power output ($\dot{W}_{PEAK}$, Watts), defined as the maximum power output achieved by a cyclist as a result of an incrementally graded exercise test to exhaustion, was maximized in the "sitting" STA in combination with the "upright" TA. It is reasonable to assume, given the vague positioning descriptions, that this position produced one of the largest HAs tested. The heterogeneous training background of the subject population, and subsequent "cross-training" effect, may explain why the larger HAs produced the highest power outputs. If the subject population tested comprised exclusively competitive cyclists, the positions producing smaller HAs would be expected to result in the highest power outputs.

The research of Origenes et al. (1993) also provided evidence of "cross-training" adaptations. Ten moderately trained males were tested in two cycling positions: 1) upright position (hands positioned on the brake-lever hoods, arms extended, elbows slightly bent), and 2) aerodynamic position (forearms positioned on the top of the aero-handlebars). Unfortunately, the HAs produced by the two experimental conditions were neither reported nor controlled. Origenes et al. found no significant differences in $\dot{V}O_{2MAX}$, maximal heart rate, or $\dot{W}_{PEAK}$. However, the training backgrounds of the participants tested were dissimilar: four triathletes, two high-altitude climbers, and four untrained, but recreationally active, individuals. It is likely that the presence of "cross-training" adaptations would explain the lack of significant differences.

Practical Applications

The difference measures $\Delta\dot{V}O_{2(Min)}$, $\Delta HR_{(Min)}$, and $\Delta\dot{V}_{e(Min)}$ attempted to explore the relationship between the position resulting in the lowest respective physiological measure for each cyclist (P_{Min}) and each of the other four experimental positions. The lowest mean $\dot{V}O_2$, HR, and $\dot{V}_e$ measures were subtracted, respectively, from those at each of the four remaining positions, using the following equations:

$$\Delta\dot{V}O_{2(Min)} = (\Delta\dot{V}O_{2SUB}\ @P_{i(Min)}) - (\Delta\dot{V}O_{2SUB}\ @P_i) \tag{15}$$

$$\Delta HR_{\ (Min)} = (\Delta HR\ @P_{i(Min)}) - (\Delta HR\ @P_i) \tag{16}$$

$$\Delta\dot{V}_{e(Min)} = (\Delta\dot{V}_e\ @P_{i(Min)}) - (\Delta\dot{V}_e\ @P_i) \tag{17}$$

$P_{i(Min)}$ is the position with the lowest respective physiological measure for each subject, and P_i refers to all five experimental positions. The result was a delta value, centered at each cyclist's P_0, that did not always result in each cyclist's P_0 producing the lowest physiological measure. A non-significant quadratic relationship was noted between $\Delta\dot{V}O_{2(Min)}$, $\Delta HR_{(Min)}$, and $\Delta\dot{V}_{e(Min)}$ across the five experimental positions (Figures 10-12). Each of the figures show that a position resulting in a change in HA of +5º produced either a similar, or a lower, respective mean physiological measure. Therefore, a position closer to P_{+5} may elicit a lower respective physiological measure than P_0 at a fixed power output for many of the cyclists who participated in the current study.

Consequently, a cyclist's P_{Min} needs to be determined before a prediction of their optimal time-trial position is made. Theoretically, a cyclist's P_{Min} should be equivalent to the position in which a cyclist also produces their maximum $\dot{W}_{VT}$. The determination of

P_{Min} would provide a cyclist with a position that would increase their $\dot{W}_{VT}$ if P_0 differed from P_{Min}. When this information is used in combination with Klippel and Heil's (2001) algorithm, it will allow a cyclist to determine the position that maximizes their ground speed during a flat time-trial.

A "cross-training" effect may have significant repercussions on a cyclist's P_{Min}, and, accordingly, their time-trial positioning "strategy." Most traditional road cyclists tend to choose the least complicated way of decreasing frontal area by simply decreasing their TA and HA. When the HAs used in other endurance sports, and the resultant "cross-training" effect, are considered, it is reasonable to assume that the HA corresponding to most cyclist's P_{Min} may be greater than that produced by their P_0. This reasoning is further supported by the previously discussed graphical evidence (Figures 10-12). Therefore, a decrease in both a cyclist's TA and HA, for time-trialing purposes, would further reduce HA from that corresponding to the cyclist's P_{Min}. As a result, the decreased HA would result in both an increase in $\dot{V}O_{2SUB}$ at a fixed power output and a decrease in maximum ground speed (Heil et al., 1997; Gnehm et al., 1997; Too, 1991; Welbergen and Clijsen, 1990).

Consequently, a case can be made for a specialization of training that has previously not been suggested. The difficulty lies in whether to increase a cyclist's HA corresponding to their P_0 to match those of other endurance sports that they might participate in, or to limit their participation in those sports in an attempt to specialize HA and increase efficiency in their P_0. For instance, it may be more appropriate to increase a triathlete's cycling HA in an attempt to utilize HAs closer to those used in running and swimming. On the other hand, it may be logical for a committed road cyclist to limit endurance training to activities using HAs similar to that corresponding to their P_0; attempting to use the "training effect" to their advantage. Likewise, it may be advantageous for time-trial specialists to train in HAs that mimic those of the position that, within limits of comfort, is most aerodynamically beneficial. Theoretically, such an approach would allow a cyclist to maximize their aerodynamic advantage while maintaining $\dot{W}_{VT}$.

Optimal Time-Trial Position

Klippel and Heil (2002) proposed a mathematical simulation that predicted a cyclist's optimal time trial position, defined by the position, or combination of STA and TA, that minimized power demand while maintaining maximal power supply. The simulation required the cyclist's STA and TA measurements in their P_0, their body mass (M_B), and $\dot{W}_{VT}$ while cycling in their P_0.

The STA and TA combination that resulted in the highest ground speed ($\dot{s}$, kph) represented the optimal time-trial position. This optimal position was an attempt to minimize the amount of power output lost through HA manipulation by reducing frontal area in such a way that HA was largely conserved. Since the goal of a time trial cyclist is to maintain the highest average speed possible, this position should maximize their performance capabilities.

A major assumption underpinning Klippel and Heil's (2002) algorithm was that the HA corresponding to P_0 was equivalent to the HA that maximized power output.

Since Heil et al. (1997) hadd not actually tested cyclists in their P_0, or systematically manipulated their HA relative to their P_0, it can only be assumed that the relationship defined by Equation 4 of the algorithm is valid:

$$\Delta\dot{V}O_{2SUB} = 0.454(\Delta HA)^2 + 0.802(\Delta HA) \tag{4}$$

Given this assumption, the example $\dot{s}$ output for a cyclist with a P_0 corresponding to a STA of 73°, a TA of 20°, and M_B of 70 kg is presented in Table 5. The maximal $\dot{s}$ occurs at the position resulting from a STA of 80º and a TA of 1º. This position reduces the cyclist's frontal area from 0.408 m^2 at a STA of 73° and a TA of 20°, to a frontal area of 0.334 m^2 at a STA of 80° and a TA of 1°. The net effect is a decrease in frontal area of 0.074 m^2, or 18% of the cyclist's P_0. Increasing STA and decreasing TA limits HA change to -3º.

When the algorithm is adjusted to take account of the relationship between HA and $\dot{V}O_{2SUB}$ defined by the current study (Figure 11), Equation 4 becomes:

$$\Delta\dot{V}O_{2SUB} = 0.0003(\Delta HA)^2 + 0.0036(\Delta HA) \tag{10}$$

The example $\dot{s}$ output for a cyclist with a P_0 corresponding to a STA of 73°, TA of 20°, and M_B of 70 kg is presented in Table 7. The maximal $\dot{s}$ occurs at the position resulting from a STA of 70º and a TA of 1º. This position reduces the cyclist's frontal area from 0.408 m^2 at a STA of 73° and a TA of 20°, to a frontal area of 0.329 m^2 at a STA of 70°

and a TA of 1°. The net effect is a decrease in frontal area of 0.079 m^2, or 19% of the cyclist's P_0. Equation 10 allows a larger amount of HA manipulation, therefore HA is reduced by 21° from the cyclist's P_0.

The revised algorithm permits a greater amount of HA manipulation than was originally suggested by Klippel and Heil (2002). The current adaptation of the algorithm makes use of the altered relationship between $\dot{W}_{VT}$ and changes in HA from that corresponding to P_0. According to Klippel and Heil's original algorithm, the HA reduction of 21º suggested in the above example would have resulted in a 73 watt reduction in $\dot{W}_{VT}$. However, the revised algorithm voids the drop in $\dot{W}_{VT}$, allowing a cyclist to choose a smaller STA than formerly suggested. The advantage of using a smaller STA is that it further reduces frontal area. Specifically, the position STA = 70º, TA = 1º suggested by the revised algorithm in the previous example resulted in an additional reduction of 0.005 m^2, or 1% of the cyclist's P_0. The final result of both the revised power output and reduction in frontal area is an increase in the cyclist's maximum ground speed ($\dot{s}$, kph). According to Klippel and Heil's original algorithm, the position STA = 70º, TA = 1º suggested by the revised algorithm should have resulted in a $\dot{s}$ of 51.4 kph. According to the revised model, this position should now result in a $\dot{s}$ of 54.5 kph, an increase of 3.1 kph.

The outcome of the revised algorithm suggests that changes in HA, resulting from changes in position, may have a lesser effect on a cyclist's power producing capabilities than previously hypothesized. Two possible implications follow: 1) it may be possible to achieve an optimal time-trial position in cross-trained cyclists by reducing their TA, and 2) the population of cyclists affected by minute changes may be much smaller and more specialized than originally suggested. It is possible that small changes in HA may only affect power producing capabilities significantly in a more elite population than was represented in the current study.

While the findings of Heil et al. (1997) and the current study may not significantly affect the general population of cyclists, the trend between HA and $\dot{V}O_{2SUB}$ should not be ignored by elite racing cyclists. Further research is needed on the effect of HA on a cyclist's power producing capabilities. Of particular importance is the effect training may have on a cyclist's $\dot{W}_{VT}$ with HAs that differ from those corresponding to P_0. For elite time-trial specialists, always attempting to reduce performance times, the implications of such a training effect could be crucial.

Table 11. Example maximal ground speed (kph) for a preferred position (P_0) corresponding to a seat tube angle (STA, degrees) of 73° and trunk angle (TA, degrees) of 20°, and body mass (M_B, kg) of 70kg. Areas highlighted are positions that elicit the highest maximal ground speed. Simulation data based on algorithm from Klippel and Heil (2002).

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	51.4	50.9	50.6	50.5	50.5	50.5	50.5	50.5	50.5	50.5	50.6	50.6	50.6	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.7	50.6	50.6	50.6	50.5	50.5	50.4	50.3	50.3
71	51.9	51.4	51.1	51.0	50.9	50.8	50.8	50.8	50.8	50.8	50.8	50.8	50.9	50.9	50.9	50.8	50.8	50.8	50.8	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.3	50.2	50.1
72	52.4	51.8	51.5	51.3	51.2	51.2	51.1	51.1	51.1	51.0	51.0	51.0	51.0	51.0	51.0	50.9	50.9	50.9	50.8	50.8	50.7	50.7	50.6	50.5	50.4	50.3	50.3	50.1	50.0	49.9
73	52.8	52.2	51.8	51.7	51.5	51.4	51.4	51.3	51.3	51.2	51.2	51.2	51.1	51.1	51.0	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.5	50.4	50.3	50.2	50.1	50.0	49.8	49.7
74	53.2	52.5	52.1	51.9	51.8	51.7	51.6	51.5	51.4	51.4	51.3	51.2	51.2	51.1	51.1	51.0	50.9	50.8	50.8	50.7	50.6	50.5	50.4	50.3	50.1	50.0	49.9	49.7	49.6	49.4
75	53.5	52.8	52.4	52.1	52.0	51.8	51.7	51.6	51.5	51.4	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.7	50.5	50.4	50.3	50.2	50.1	49.9	49.8	49.6	49.4	49.3	49.1
76	53.7	53.0	52.6	52.3	52.1	51.9	51.8	51.7	51.6	51.5	51.4	51.3	51.2	51.1	51.0	50.9	50.8	50.6	50.5	50.4	50.3	50.1	50.0	49.8	49.6	49.5	49.3	49.1	48.9	48.7
77	53.9	53.1	52.7	52.4	52.2	52.0	51.9	51.7	51.6	51.5	51.4	51.2	51.1	51.0	50.9	50.7	50.6	50.5	50.3	50.2	50.0	49.9	49.7	49.5	49.3	49.1	48.9	48.7	48.5	48.3
78	54.0	53.3	52.8	52.5	52.3	52.1	51.9	51.7	51.6	51.4	51.3	51.2	51.0	50.9	50.7	50.6	50.4	50.3	50.1	49.9	49.8	49.6	49.4	49.2	49.0	48.8	48.5	48.3	48.1	47.8
79	54.1	53.3	52.9	52.5	52.3	52.1	51.9	51.7	51.5	51.3	51.2	51.0	50.9	50.7	50.5	50.4	50.2	50.0	49.8	49.6	49.4	49.2	49.0	48.8	48.6	48.3	48.1	47.8	47.6	47.3
80	54.2	53.4	52.9	52.5	52.2	52.0	51.8	51.6	51.4	51.2	51.0	50.8	50.7	50.5	50.3	50.1	49.9	49.7	49.5	49.3	49.1	48.8	48.6	48.3	48.1	47.8	47.6	47.3	47.0	46.7
81	54.2	53.3	52.8	52.5	52.1	51.9	51.6	51.4	51.2	51.0	50.8	50.6	50.4	50.2	50.0	49.8	49.6	49.3	49.1	48.9	48.6	48.4	48.1	47.8	47.6	47.3	47.0	46.7	46.4	46.0
82	54.1	53.3	52.7	52.3	52.0	51.7	51.5	51.2	51.0	50.8	50.6	50.3	50.1	49.9	49.7	49.4	49.2	48.9	48.7	48.4	48.2	47.9	47.6	47.3	47.0	46.7	46.4	46.0	45.6	45.3
83	54.0	53.2	52.6	52.2	51.8	51.6	51.3	51.0	50.7	50.5	50.3	50.0	49.8	49.5	49.3	49.0	48.7	48.5	48.2	47.9	47.6	47.3	47.0	46.7	46.3	46.0	45.6	45.3	44.9	44.5
84	53.9	53.0	52.4	52.0	51.6	51.3	51.0	50.7	50.4	50.2	49.9	49.6	49.4	49.1	48.8	48.5	48.3	48.0	47.6	47.3	47.0	46.7	46.4	46.0	45.6	45.2	44.9	44.4	44.0	43.6
85	53.7	52.8	52.2	51.8	51.4	51.0	50.7	50.4	50.1	49.8	49.5	49.2	48.9	48.6	48.3	48.0	47.7	47.4	47.1	46.7	46.4	46.0	45.6	45.2	44.8	44.4	44.0	43.5	43.1	42.6
86	53.5	52.5	51.9	51.4	51.0	50.7	50.3	50.0	49.7	49.4	49.1	48.7	48.4	48.1	47.8	47.4	47.1	46.7	46.4	46.0	45.6	45.2	44.8	44.4	44.0	43.5	43.0	42.5	42.0	41.5
87	53.2	52.2	51.6	51.1	50.7	50.3	49.9	49.6	49.2	48.9	48.5	48.2	47.9	47.5	47.1	46.8	46.4	46.0	45.6	45.2	44.8	44.4	43.9	43.5	43.0	42.5	42.0	41.4	40.8	40.2
88	52.8	51.9	51.2	50.7	50.2	49.8	49.4	49.1	48.7	48.3	48.0	47.6	47.2	46.9	46.5	46.1	45.7	45.3	44.8	44.4	43.9	43.4	42.9	42.4	41.9	41.4	40.8	40.2	39.5	38.9
89	52.5	51.4	50.8	50.2	49.8	49.3	48.9	48.5	48.1	47.7	47.3	46.9	46.5	46.1	45.7	45.3	44.8	44.4	43.9	43.4	42.9	42.4	41.9	41.3	40.7	40.1	39.5	38.8	38.1	37.3
90	52.0	51.0	50.3	49.7	49.2	48.8	48.3	47.9	47.5	47.1	46.6	46.2	45.8	45.3	44.9	44.4	43.9	43.4	42.9	42.4	41.8	41.3	40.7	40.0	39.4	38.7	38.0	37.2	36.4	35.6

Table 12. Example maximal ground speed (kph) for a preferred position (P_0) corresponding to a seat tube angle (STA, degrees) of 73° and trunk angle (TA, degrees) of 20°, and body mass (M_B, kg) of 70kg. Areas highlighted are positions that elicit the highest maximal ground speed. Simulation data based on algorithm from current study.

Trunk Angle (degrees)

Seat Tube Angle (degrees)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
70	54.5	53.7	53.2	52.8	52.5	52.3	52.1	52.0	51.8	51.7	51.6	51.5	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.4	50.3
71	54.5	53.6	53.1	52.8	52.5	52.3	52.1	51.9	51.8	51.7	51.5	51.4	51.3	51.2	51.2	51.1	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.4	50.3	50.3
72	54.4	53.6	53.1	52.7	52.5	52.3	52.1	51.9	51.8	51.6	51.5	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.8	50.7	50.7	50.6	50.5	50.5	50.5	50.4	50.4	50.3	50.3
73	54.4	53.6	53.1	52.7	52.4	52.2	52.0	51.9	51.7	51.6	51.5	51.4	51.3	51.2	51.1	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2
74	54.4	53.5	53.0	52.7	52.4	52.2	52.0	51.8	51.7	51.6	51.4	51.3	51.2	51.2	51.1	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.3	50.2
75	54.3	53.5	53.0	52.7	52.4	52.2	52.0	51.8	51.7	51.5	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2	50.2
76	54.3	53.5	53.0	52.6	52.4	52.1	51.9	51.8	51.6	51.5	51.4	51.3	51.2	51.1	51.0	50.9	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.2
77	54.3	53.4	53.0	52.6	52.3	52.1	51.9	51.8	51.6	51.5	51.4	51.2	51.2	51.1	51.0	50.9	50.8	50.8	50.7	50.6	50.6	50.5	50.5	50.4	50.3	50.3	50.3	50.2	50.2	50.1
78	54.3	53.4	52.9	52.6	52.3	52.1	51.9	51.7	51.6	51.4	51.3	51.2	51.1	51.0	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.1	50.1
79	54.2	53.4	52.9	52.5	52.3	52.0	51.9	51.7	51.6	51.4	51.3	51.2	51.1	51.0	50.9	50.9	50.8	50.7	50.6	50.6	50.5	50.5	50.4	50.3	50.3	50.3	50.2	50.1	50.1	50.1
80	54.2	53.4	52.9	52.5	52.2	52.0	51.8	51.7	51.5	51.4	51.3	51.2	51.1	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0
81	54.2	53.3	52.8	52.5	52.2	52.0	51.8	51.6	51.5	51.4	51.2	51.1	51.0	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.1	50.0
82	54.1	53.3	52.8	52.5	52.2	52.0	51.8	51.6	51.5	51.3	51.2	51.1	51.0	50.9	50.8	50.8	50.7	50.6	50.5	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0
83	54.1	53.3	52.8	52.4	52.2	51.9	51.8	51.6	51.4	51.3	51.2	51.1	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.5	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	50.0
84	54.1	53.3	52.8	52.4	52.1	51.9	51.7	51.6	51.4	51.3	51.2	51.1	51.0	50.9	50.8	50.7	50.6	50.6	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	49.9
85	54.1	53.2	52.7	52.4	52.1	51.9	51.7	51.5	51.4	51.3	51.1	51.0	50.9	50.9	50.8	50.7	50.6	50.5	50.5	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	50.0	49.9
86	54.1	53.2	52.7	52.4	52.1	51.9	51.7	51.5	51.4	51.2	51.1	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.4	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	49.9	49.9
87	54.0	53.2	52.7	52.3	52.1	51.8	51.6	51.5	51.3	51.2	51.1	51.0	50.9	50.8	50.7	50.6	50.6	50.5	50.4	50.4	50.3	50.2	50.2	50.1	50.1	50.0	50.0	50.0	49.9	49.9
88	54.0	53.2	52.7	52.3	52.0	51.8	51.6	51.5	51.3	51.2	51.1	51.0	50.9	50.8	50.7	50.6	50.5	50.5	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	49.9	49.9	49.8
89	54.0	53.1	52.6	52.3	52.0	51.8	51.6	51.4	51.3	51.2	51.0	50.9	50.8	50.7	50.7	50.6	50.5	50.4	50.4	50.3	50.2	50.2	50.1	50.1	50.0	50.0	49.9	49.9	49.8	49.8
90	53.9	53.1	52.6	52.3	52.0	51.8	51.6	51.4	51.3	51.1	51.0	50.9	50.8	50.7	50.6	50.6	50.5	50.4	50.3	50.3	50.2	50.2	50.1	50.1	50.0	50.0	49.9	49.9	49.8	49.8

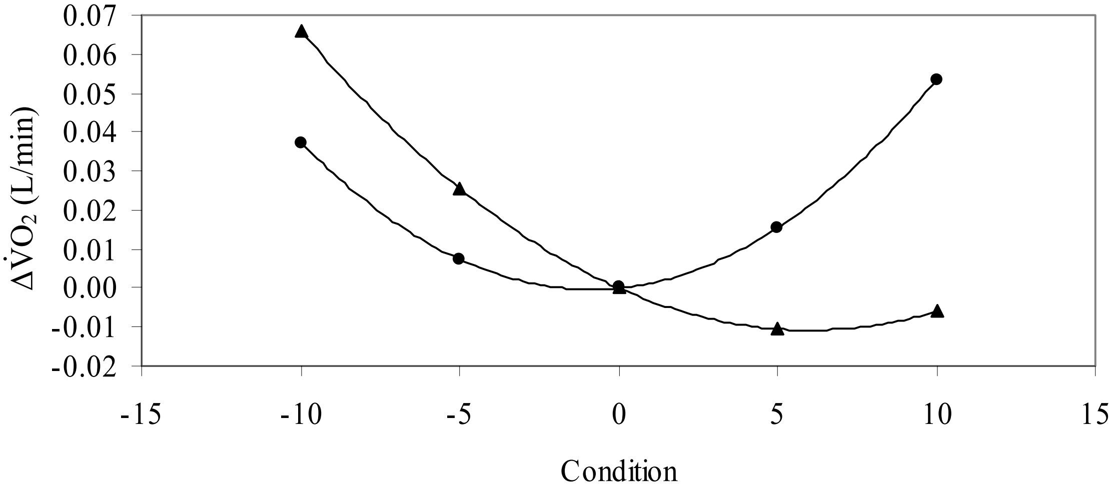

Figure 9. Scatterplot depicts comparison of relationships between mean delta oxygen consumption (ΔVO_2) and experimental position from Heil et al. (1997) and current study. Solid line (▲) is a polynomial trend line predicted by current study: ΔVO_2 (l/min) = $0.0003(\Delta HA)^2-0.0036(\Delta HA)$. Solid line (●) is a polynomial trend line predicted by Heil et al. (1997): $\Delta VO2$ (l/min) = $0.000454(\Delta HA)^2 +0.000802(\Delta HA)$.

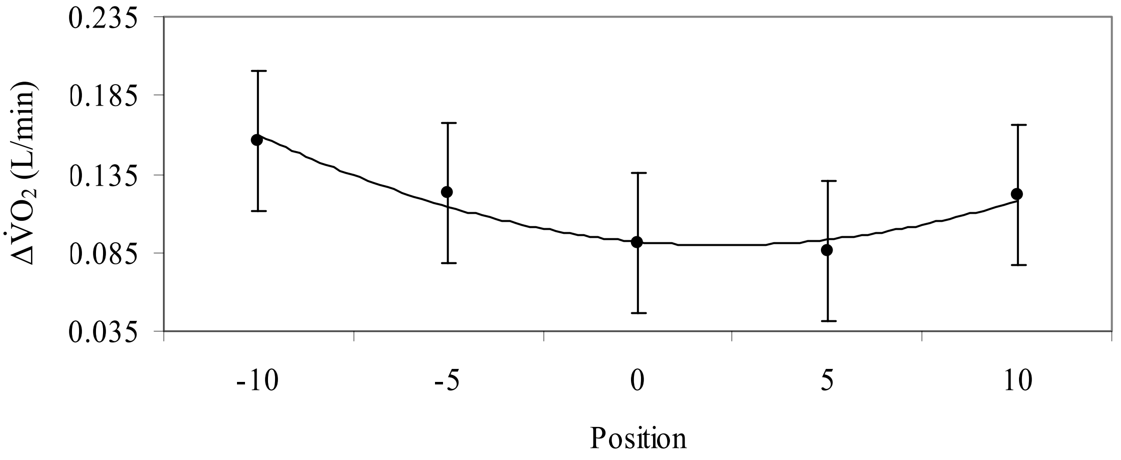

Figure 10. Scatterplot depicts relationship between mean delta oxygen consumption (ΔVO_2) and position. Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline based on mean data values: ΔVO_2 (l/min) = $0.0117(\Delta HA)^2-0.0809(\Delta HA)+0.229$ ($R^2= 0.043$, SEE = ±0.04 L/min, $p = 0.2282$, $n = 5$).

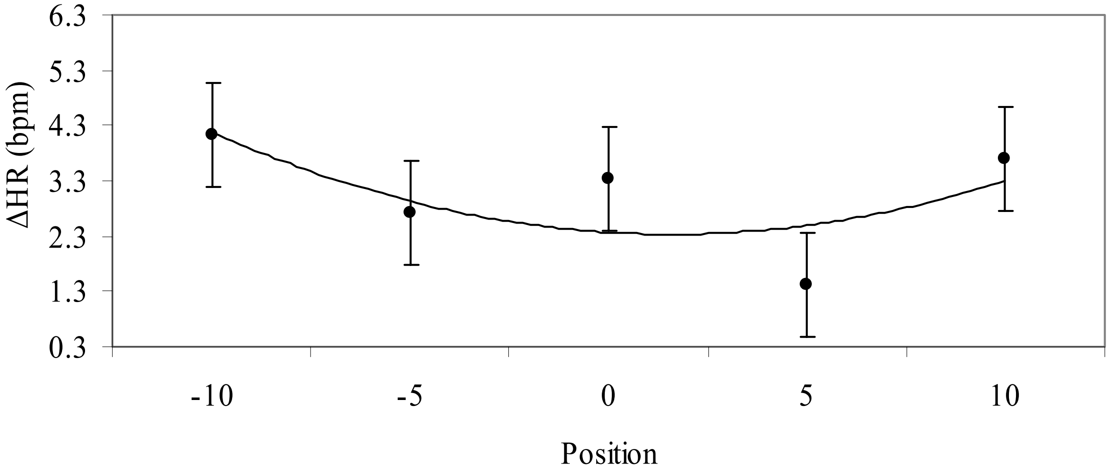

Figure 11. Scatterplot depicts relationship between mean heart rate (HR) and position. Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline based on mean data values: ΔHR (bpm) = $0.3437(\Delta HA)^2-2.2812(\Delta HA)+6.1187$. ($R^2 = 0.009$, SEE = ±0.94 bpm, $p = 0.0499$, $n = 5$).

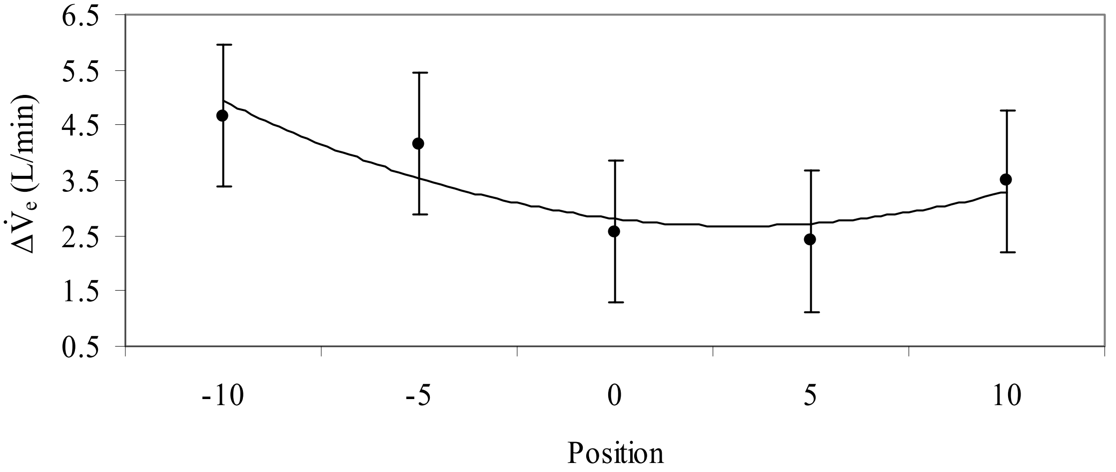

Figure 12. Scatterplot depicts relationship between mean minute ventilation (V_e) and position. Error bars represent standard error for comparison from Tukey's post-hoc analysis ($p > 0.01$). Solid line is a polynomial trendline based on mean data values: ΔV_e (l/min) = $0.3284(\Delta HA)^2-2.3792(\Delta HA)+6.9844$. ($R^2 = 0.025$, SEE = ±1.3 L/min, $p = 0.3396$, $n = 5$).

CHAPTER 6

CONCLUSIONS

It has been determined through the current study that physiological measures do not increase in trained collegiate cyclists when hip angle (HA) is manipulated within ±10º of that corresponding to a cyclist's preferred position (P_0). No significant differences were found between HA conditions for oxygen consumption ($\dot{V}O_2$), minute ventilation ($\dot{V}_e$), or heart rate.

While somewhat specialized, the population of cyclists tested in the current study were involved in various endurance sports, such as nordic skiing and mountain bicycling. Both of these sports involve HAs that are larger than those common to competitive cycling. As a result, the "training effect" from participating in these sports seems to result in a greater efficiency in larger HAs, thereby limiting their comparability with a professional cyclist.

The lack of significant differences between conditions indicates that the prediction equation created by Klippel and Heil (2002) may not be applicable to recreationally trained cyclists. The basis of the algorithm was that, in general, a position using an increased seat tube angle (STA) and a decreased trunk angle (TA), while maintaining HA, would result in a time trial position that maximized ground speed. This position would represent the optimal balance between a cyclist's power output and frontal area. Klippel and Heil's algorithm assumed a relationship between a cyclist's HA and submaximal oxygen consumption ($\dot{V}O_{2SUB}$) similar to that suggested by Heil et al.

(1997). The algorithm revision suggested in the current study, on the other hand, would support the proposition that, in the population tested, a position using a decreased TA would result in a time trial position that maximized ground speed. The implication is that the traditional method of decreasing frontal area, by decreasing TA and HA, may be the most practical and least disruptive for a population similar to that tested.

A non-significant quadratic trend between HA and physiological measures, similar to that of Heil et al. (1997) was noted. While not significant in the population tested, such a trend may prove noteworthy in a more highly trained and sport specific population, such as professional racing cyclists. The algorithm presented by Klippel and Heil (2002) may prove more applicable in determining optimal time trial positions for professional cyclists. Further research is needed to confirm whether or not HA manipulation has a significant influence on $\dot{V}O_{2SUB}$ in a more specialized cycling population.

If a significant relationship were found between HA and $\dot{V}O_{2SUB}$ in professional cyclists it would have a significant impact in a world class competition. In the 2002 World Time Trial Championship, the substantial difference between first (48 min 8 sec) and last (57th place, 55 min 5 sec) was equivalent to 14.4% of total time. However, when first is compared with second place (48 min 16 sec), the time difference drops to a mere 0.3% of total time. It is possible that such a 0.3% discrepancy could be accounted for by a variance in the selection of a cyclist’s helmet, tires, or, more importantly, aerodynamic position. While not statistically significant, the trends demonstrated in this study provide an argument for further investigation in a more highly trained and sport specific population.

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APPENDICES

APPENDIX A

SUBJECT CONSENT FORM

SUBJECT CONSENT FORM

FOR

PARTICIPATION IN HUMAN SUBJECT RESEARCH

MONTANA STATE UNIVERSITY

PROJECT TITLE: The Effects of Hip Angle Manipulation on Submaximal Oxygen Consumption in Collegiate Male Cyclists.

PROJECT DIRECTOR:
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FUNDING: This project is not funded.

Health Screening Prior to Testing

Prior to testing, each participant is required to read and sign the Subject Consent Form. In addition, each individual willing to participate in this study must receive clearance by filling out the **Health Status Questionnaire**. If deemed appropriate by the Project Director and Project Supervisor, the information given may automatically disqualify you from participating in this study without further clearance from your physician. This procedure is in compliance with policies formulated by the American College of Sports Medicine[1]

Purpose

You are being asked to participate in a study to define the relationship between a cyclist's hip angle and submaximal oxygen consumption. The information gained from this study

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[1] American College of Sports Medicine (2000). *ACSM's Guidelines for Exercise Testing and Prescription* (6th edition). Williams & Wilkins, Philadelphia, Pa.

will be used to further refine an algorithm created to predict a cyclist's optimal time-trial position.

Procedures

If you agree to participate in this study, you will be involved in three testing sessions. These testing sessions will include collection of anthropometric measures, physiological data, and filming (for kinematic analysis). You will also be asked to ride a cycle ergometer in five variations of your preferred riding position. During all testing sessions, you will be asked to provide your personal cycling shoes, and racing clothing. You will be asked to provide your personal bicycle for the first and third testing sessions.

The first session will last no longer than 2 hours. It will involve taking anthropometric measurements of your preferred riding position while riding your personal bicycle attached to a stationary trainer. It will also include manipulation of your position, using a cycle ergometer, to create four additional experimental positions. Two of these positions will result in a hip angle greater than your preferred riding position, and two will result in hip angles less that your preferred riding position. Additionally, this appointment will include riding on a cycle ergometer for five minutes in each of the five previously mentioned positions at a self-chosen power output. Concurrently, the final two minutes of riding in each of the five positions will be filmed for kinematic analysis. In addition, a digital photograph will be taken in each of the five positions in order to determine actual frontal area.

The second session will last no more than 1 hour. It will consist of a maximal cycling test to determine your maximal oxygen consumption (VO_{2MAX}) and power output at your ventilatory threshold. A warm-up of fifteen minutes will take place prior to the start of the test, and will include calibration of the cycle ergometer. The maximal cycling test will last anywhere from 5-17 minutes. The purpose of this test is to elicit maximal results, and therefore you will be encouraged to continue as long as possible. The test will end when either you signal that you can no longer continue, or your cadence drops $\geq$5 rpm for 5 sec. or more.

The third session will take no longer than 2 hours. It will consist of measuring oxygen consumption in 10 riding conditions. These conditions will consist of two different power outputs in both your preferred riding position and each of the four experimental positions determined in the first testing session. The two power outputs will be equivalent to 75% and 95% of your ventilatory threshold (VT), or sustainable maximum. The principal investigator will determine your VT using the results from your second visit. Prior to the start of the testing, a ten minute warm-up will take place. Following the warm-up, you will be asked to ride for 8 minutes in each position, 5 minutes at 75% of your VT, immediately followed by 3 minutes at 95% of your VT for a total riding time of 50 minutes. The remainder of the time will be needed for set-up and adjustment of the cycle ergometer.

During the second and third testing sessions, the air you breathe during your riding will be analyzed in order to calculate oxygen consumption. In order to accomplish this you will be required to breath exclusively via a mouthpiece and tubing into a metabolic analyzer. During this testing your heart rate responses to the exercise will be recorded. You will also be asked to wear a telemetry-based Polar heart rate monitor consisting of an elastic chest strap and wristwatch. During all testing taking place on the cycle ergometer you will use your personal pedals, shoes, and clothing.

Confidentiality

All data collected will remain confidential. Your data will be identified by code and only the Project Director will have access to this code. Your name will not be used in connection with any part of this study. All photographic and filming data will be identified by code and kept on a secured computer. All hardcopies of photographic and film originals will be permanently stored in a locked and secure storage cabinet in the Movement Science Laboratory. Photographic and film originals may be reanalyzed for future studies. Only the Project Director will have access to photographic and film data.

Risk

The risks for participating in this study are those assumed with riding a bicycle at maximal effort. You should be aware that a VO_{2MAX} test may cause extreme fatigue immediately following the test and possibly throughout the next day. Those who are less accustomed to high-intensity aerobic exercise are likely to experience extreme fatigue following the test. VO_{2MAX} testing 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 slight (less than 1 in 10,000), since you are in good physical condition with no known symptoms of heart disease, and since the test will be directed by trained personnel. The measuring devices (heart rate monitor and mouthpiece) may feel somewhat restrictive and/or uncomfortable during testing, but all possible adjustments will be made to achieve maximal comfort.

Benefits

Each participant will be provided with the results of their maximal cycling test. In addition, participants will be provided with an estimate of their optimal time-trial position based on an algorithm created by the Montana State University Movement Science Laboratory. This information, and a report of the findings of this research study, can be acquired by contacting the Project Director, Nathan Klippel, by phone (406-994-6325) or by e-mail (nathanklippel@peoplepc.com).

Freedom of Consent

You may withdraw consent for participation in writing, by telephone, or in person without prejudice. Please contact the primary investigator, Nathan Klippel, by phone

406-994-6325 or by E-mail *nathanklippel@peoplepc.com* to discontinue participation. *Participation in this study is completely voluntary.*

Injury and Compensation

In the UNLIKELY event that your participation in this project results in physical injury to you, the primary investigator will assist and advise 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 your participation in this project. Neither the primary investigator nor Montana State University will provide financial compensation for injury that may occur as a result of your participation in this study. In addition, 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 Montana State University. *Further information regarding medical treatment may be obtained by calling the primary investigator, Nathan Klippel at 406-994-6325.* You are encouraged to express any questions, doubts, or concerns regarding this project. The primary investigator fully intends to conduct this study with your best interest, safety, and comfort in mind.

The Human Subjects Committee, Montana State University, Bozeman, Montana has reviewed this project. *The Chairman of the Human Subjects Committee, Montana State University, Mark Quinn, 406-994-5721*, can answer additional questions concerning the rights of human subjects.

THE EFFECT OF HIP ANGLE MANIPULATION ON SUBMAXIMAL OXYGEN CONSUMPTION IN COLLEGIATE CYCLISTS

Statement of Authorization

I, *the participant*, have read the Informed Consent Document and understand 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 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 legal participant, are **less than 18 years of age** 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 legal minor signed above as _____________________ (*stated relationship to the minor*), agree to the participation of __________________________________ (*print* *name of minor*) in the project described in the preceding pages. I understand that I may later refuse participation in this project and that the legal minor, through his/her own action or mine, may withdraw from the study at any time.

Signed: ____ Date:___________________

Parent or legal Guardian

APPENDIX B

PHYSIOLOGICAL AND KINEMATIC DATA

Table 13. Table of raw data.

Subject	Gender	Height (in)	Weight (kg)	VO2MAX (L/min)	Calculated VT (L/min)	Maximum Power (watts)	Power at VT (watts)	Condition	VO2 (L/min)	HR (bpm)	Ve (L/min)	HA	TA	KA	AA
1	Male	74	78	4.973	4.104	360	220	-10	3.2395	186	75.75	58.968	34.421	94.738	96.591
								-5	3.462	189.5	79.75	63.896	30.381	94.206	97.166
								0	3.2855	191.5	76.6	65.056	34.196	90.844	92.113
								5	3.4005	181	83.05	65.161	33.142	92.711	95.826
								10	3.387	188.5	82.95	65.98	31.167	90.46	99.535
2	Male	72	75	4.917	4.054	390	270	-10	3.089	139	51.95	47.516	33.864	93.578	132.685
								-5	3.0225	138.5	53.5	48.379	35.676	90.966	136.972
								0	3.035	138.5	54.45	59.124	35.576	95.118	133.746
								5	3.1105	141.5	56.25	60.948	36.529	93.429	132.053
								10	3.096	138.5	49.35	65.1	36.01	96.773	127.305
3	Male	71	72	4.592	4.098	390	310	-10	3.588	172.5	80.95	54.913	27.018	99.862	107.844
								-5	3.75	161	85.85	56.783	27.793	99.323	106.598
								0	3.408	170.5	72.55	59.273	29.556	95.705	108.275
								5	3.4915	171	73.75	63.98	28.91	90.434	105.451
								10	3.4415	169.5	70.05	67.84	29.711	95.505	106.308
4	Male	73	78	4.42	3.692	360	280	-10	3.1825	163	61.95	56.968	38.962	97.251	129.128
								-5	3.177	164	60.1	58.123	35.982	90.917	131.801
								0	3.08	164.5	59.45	62.578	38.036	95.057	128.498
								5	3.1865	160.5	63.3	69.525	35.643	91.482	126.407
								10	3.161	164.5	61.6	71.459	39.167	93.371	131.636
5	Male	68	76	4.6	3.805	390	280	-10	3.292	150.5	70.2	48.081	32.898	95.072	123.234
								-5	3.143	151.5	66.7	49.896	30.24	93.771	123.026
								0	3.2205	152	69.45	54.049	29.442	96.485	122.828
								5	3.1755	146	66.3	64.545	31.133	92.679	119.136
								10	3.219	152.5	72.55	65.013	32.809	89.566	119.033

Table 13. Table of raw data (continued).

Subject	Gender	Height (in)	Weight (kg)	VO2MAX (L/min)	Calculated VT (L/min)	Maximum Power (watts)	Power at VT (watts)	Condition	VO2 (L/min)	HR (bpm)	Ve (L/min)	HA	TA	KA	AA
6	Female	66	62	3.535	2.481	270	230	-10	2.8035	167.5	61.3	53.595	36.267	85.232	114.201
								-5	2.55	165	57.6	56.699	38.049	89.517	116.822
								0	2.616	165	58.9	61.526	36.764	89.292	113.067
								5	2.446	164	53.05	65.867	39.419	83.239	116.58
								10	2.7455	168.5	67.45	67.43	37.944	88.086	119.282
7	Male	69.5	72	4.523	3.719	360	260	-10	3.3905	144.5	71.15	52.389	28.03	90.428	111.809
								-5	3.3525	136	66.95	55.915	27.401	93.466	114.568
								0	3.1735	137	61.4	59.779	30.959	87.016	111.441
								5	3.173	134.5	60.1	61.14	28.173	89.579	112.609
								10	3.052	138.5	60.25	68.931	30.325	88.662	115.599
8	Male	69	72	4.463	3.886	340	260	-10	3.322	164.5	65.65	50.425	39.123	88.397	128.56
								-5	3.179	164	59.7	58.624	39.364	92.003	129.755
								0	3.289	166.5	61.1	61.882	37.802	92.789	132.291
								5	3.401	163.5	67.75	65.981	42.067	95.997	129.224
								10	3.2545	166.5	61.4	72.635	40.511	84.199	128.354
9	Male	70	71	4.886	4.548	410	340	-10	4.1025	170.5	84.85	54.258	34.221	94.656	115.632
								-5	3.967	170	86.45	57.868	36.407	89.092	118.343
								0	3.995	173.5	88.35	59.947	33.821	91.065	116.787
								5	4.035	170.5	86.5	64.529	33.967	91.756	114.341
								10	4.0345	170	87.65	68.563	36.484	87.675	118.554
10	Male	69	84	4.697	3.939	410	290	-10	3.356	162.5	51.85	51.802	34.162	99.112	115.075
								-5	3.7255	168.5	60.85	60.018	34.011	96.522	110.164
								0	3.739	162	57.65	60.38	37.767	93.597	114.763
								5	3.4565	162.5	51.35	61.401	36.155	94.615	118.729
								10	3.5695	167	59.1	70.571	34.973	99.538	110.216

Table 13. Table of raw data (continued).

Subject	Gender	Height (in)	Weight (kg)	VO2MAX (L/min)	Calculated VT (L/min)	Maximum Power (watts)	Power at VT (watts)	Condition	VO2 (L/min)	HR (bpm)	Ve (L/min)	HA	TA	KA	AA
11	Male	72	81	4.755	4.217	410	320	-10	3.448	165	60.75	58.855	35.424	97.65	119.554
								-5	3.5045	161	64.3	58.989	34.288	95.914	118.43
								0	3.6655	164	62.5	65.708	35.534	95.55	118.03
								5	3.4945	164.5	59.25	71.131	37.214	94.492	121.438
								10	3.4885	165.5	60.5	71.338	34.296	93.238	119.552
12	Male	69	72	4.396	4.138	410	360	-10	3.859	157.5	90.9	60.88	37.919	88.668	110.257
								-5	3.986	158.5	95.1	61.339	41.967	89.061	115.772
								0	3.8755	156	91.1	63.673	41.569	89.641	115.859
								5	3.826	156	91.95	64.656	35.837	86.274	110.771
								10	3.8515	158	96	64.765	36.124	83.512	113.491
13	Male	71	78	4.736	3.98	390	280	-10	3.3705	153	65.5	44.116	18.399	92.916	115.921
								-5	3.445	152	64.55	45.631	20.992	91.08	112.452
								0	3.344	151	63	46.102	19.725	90.117	117.042
								5	3.2855	149.5	60.15	53.028	20.271	88.01	116.065
								10	3.393	149.5	62.85	58.401	20.65	90.558	111.989
14	Male	70	68	4.622	3.954	360	320	-10	3.6935	161.5	80.3	51.43	29.959	93.847	110.992
								-5	3.2695	153	67.15	55.824	30.401	96.777	112.262
								0	3.241	149.5	67.4	59.103	32.988	96.239	115.675
								5	3.4295	154.5	66.05	59.386	32.461	90.414	113.439
								10	3.3215	149.5	64.85	62.033	30.717	92.919	112.87
15	Male	70	65	4.415	4.071	410	340	-10	3.2775	159	59.6	58.112	36.421	89.079	106.049
								-5	3.1435	163.5	60.25	58.312	37.43	90.146	110.573
								0	3.184	163	59	61.744	39.274	88.029	110.285
								5	3.1715	157.5	60.45	67.602	39.074	87.408	104.478
								10	3.0155	160.5	57.2	69.905	38.829	87.098	110.768

Table 13. Table of raw data (continued).

Subject	Gender	Height (in)	Weight (kg)	VO2MAX (L/min)	Calculated VT (L/min)	Maximum Power (watts)	Power at VT (watts)	Condition	VO2 (L/min)	HR (bpm)	Ve (L/min)	HA	TA	KA	AA
16	Male	67	70.5	4.279	2.05	310	160	-10	2.6305	158.5	51.85	51.007	31.359	88.418	112.925
								-5	2.4435	156.5	47.6	51.116	32.727	87.04	114.863
								0	2.4495	158	48.25	52.886	30.995	88.676	114.385
								5	2.452	154.5	49.1	55.406	32.021	88.138	120.646
								10	2.462	161	52.05	60.011	32.091	87.102	119.417