Physiologic responses to cycling with an Exo Powercam crank compared to a standard crank
by Esther Maureen Fishbaugh

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physical Education
Montana State University

Abstract:
The Exo Powercam (PC) crank purportedly allows a cyclist to pedal a bicycle at a slower cadence and larger gear than the standard crank (SC) without sacrificing power output. If this were true, physiologic responses in oxygen consumption and heart rate should decrease and/or performance should increase.

A two-part investigation was designed to test the performance of the PC against the SC. The first part, a series of three rides for each crank, tested whether performance had reached a steady state so that an accurate comparison could be made between crank mechanisms. Once a steady state was achieved, absolute oxygen uptake was compared between cranks for identical workloads.

The second part of the study measured performance between cranks in a time trial race. A transition to treadmill running immediately followed each time trial to simulate a triathlon switch from cycling to running.

The evaluation of the ride series showed no significant difference in rate of learning between the PC and the SC in either oxygen consumption ($P = 0.13$) or heart rate ($P = 0.49$). The absolute oxygen consumption of ride three demonstrated no significant difference between the cranks (mean oxygen uptake, SC = 2.27 1/min, PC = 2.26 1/min, $T = 0.3167$, $P = 0.76$).

Elapsed time for the time trial race was nearly identical between cranks (SC = 66.86 minutes, PC = 66.90 minutes, $T = -0.0421$, $P = 0.97$). Oxygen consumption, heart rate and relative perceived exertion also exhibited no significant difference at the $P < 0.05$ level, nor was the oxygen uptake for the treadmill runs significantly different. However, a subgroup of cyclists who were conditioned through running had faster elapsed time on the PC with less oxygen uptake (mean elapsed time, SC = 72.24 minutes, PC = 69.21 minutes; mean oxygen uptake, SC = 2.17 1/min, PC = 2.10 1/min).

While the PC did not exhibit improvement in the measured physiologic or performance parameters when compared to the SC, neither did it exhibit a decrease. However, runners did show improvement with the PC.

In light of its comparable performance to the SC, the PC deserves further study with more precise adjustments to the cam. Also, the PC should be tested with a larger group of runners.

PHYSIOLOGIC RESPONSES TO CYCLING WITH AN EXO POWERCAM CRANK COMPARED TO A STANDARD CRANK

by

Esther Maureen Fishbaugh

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Physical Education

MONTANA STATE UNIVERSITY
Bozeman, Montana

March, 1991

APPROVAL

of a thesis submitted by

Esther Maureen Fishbaugh

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

March 7, 1991
Date

R. Schwarzkopf
Chairperson, Graduate Committee

Approved for the Major Department

March 20, 1991
Date

Head, Major Department

Approved for the College of Graduate Studies

April 10, 1991
Date

Henry L Parsons
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted by the copyright holder.

Signature Esther M. Fishbaugh
Date March 5, 1991

ACKNOWLEDGMENTS

I wish to express my appreciation to Larry G. Brown and Houdaille Industries, Incorporated for their contribution of the two Exo Powercams, two Road Machine wind trainers and two Windtamer bicycle frames used in this experiment.

Special thanks also to Carol Bittinger, Dr. Robert Boik and Linda Steele for their many hours of effort to clarify statistics and graphs for me.

TABLE OF CONTENTS

Page

LIST OF TABLES.................................... vii

LIST OF FIGURES................................... viii

ABSTRACT.. ix

1. INTRODUCTION................................... 1

   - Problem Statement............................ 2
   - Hypothesis................................... 2
   - Limitations.................................. 2
   - Delimitations................................ 3
   - Definitions.................................. 3

2. REVIEW OF RELATED LITERATURE................... 7

   - Development of the Exo Powercam.............. 7
   - Theoretical Validity of Claims............... 11
     - Cadence.................................. 11
     - Pedal Resistance......................... 14
     - Blood Flow............................... 15
     - Relative Perceived Exertion (RPE)....... 18
   - Application of Theories...................... 22

3. METHODS.. 24

   - Subjects..................................... 25
   - Equipment.................................... 25
     - Bicycle.................................. 25
     - Gas Analysis............................. 27
     - Heart Rate............................... 27
     - Treadmill................................ 27
   - Procedures for Phase I....................... 28
     - Pilot Test to Determine Workload........ 28
     - Test Protocol, Phase I................... 29
     - Statistical Design for Phase I.......... 30
   - Procedures for Phase II...................... 30
     - Pilot Test............................... 30
     - Workload................................. 31
     - Test Protocol, Phase II.................. 31
     - Statistical Design for Phase II......... 32

TABLE OF CONTENTS--Continued

Page

4. RESULTS.......... 33

Introduction.......... 33
Phase I, Learning Curve.......... 34
Oxygen Consumption.......... 34
Heart Rate.......... 37
Gear Ratio.......... 40
Phase II, Time Trial.......... 41
Oxygen Consumption and Heart Rate.......... 41
Relative Perceived Exertion.......... 44
Elapsed Time.......... 44

5. DISCUSSION.......... 47

Introduction.......... 47
Learning Time.......... 47
Benefit for Triathletes.......... 50
Improved Efficiency.......... 50
Natural Human Motion.......... 51
Misdirected Application of Forces.......... 52
Cadence.......... 52

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS.......... 56

Summary.......... 56
Conclusions.......... 57
Recommendations.......... 58

BIBLIOGRAPHY.......... 59

APPENDICES.......... 64

Appendix A-Sample Forms.......... 65
Subject Questionnaire.......... 66
Consent Form.......... 67
Appendix B-Test Protocols.......... 68
Phase I Protocol.......... 69
Phase II Protocol.......... 70
Gas Analysis Calculations.......... 71

LIST OF TABLES

Table Page

1 Characteristics of subjects for Phase I testing.............................. 26

2 Characteristics of subjects for Phase II testing.............................. 26

3 Gear ratio (GR) and mean cadence used by each subject for each crank.............. 29

4 Mean oxygen consumption (± SE) for each ride for each crank................... 35

5 Paired t analysis of mean oxygen consumption for ride three between the cranks................................... 37

6 Mean HR (± SE) for each ride for each crank...................................... 38

7 Paired t analysis with correlations comparing mean oxygen consumption and mean heart rate (HR) between the 40K time trial for each crank and mean oxygen consumption for their corresponding treadmill run.............................. 41

LIST OF FIGURES

Figure		Page
1	Exo Powercam crank designed and manufactured by Larry G. Brown.............	5
2	Comparison of improvement in means (± SE) for oxygen consumption between rides in a series................................	36
3	Comparison of improvement in heart rate (HR) means (± SE) for rides in a series (correction factor not added; see text, page 40)................................	39
4	Comparison of means (± SD) for gear ratio between cranks for the ride series.........	42
5	Comparison of means (± SD) for oxygen consumption during the 40K time trials......	42
6	Comparison of means (± SD) for heart rate (HR) during 40K time trials................	43
7	Comparison of means (± SD) for oxygen consumption during the treadmill runs following the 40K time trials..............	43
8	Comparison of means (± SD) for relative perceived exertion (RPE) during 40K time trials...................................	45
9	Comparison of means (± SD) for elapsed time for the 40K time trials...............	45
10	Comparison of means for elapsed time for the 40K time trials for athletes who trained by running only (n = 2).........	46
11	Comparison of means for oxygen consumption for the 40K time trials for athletes who trained by running only (n = 2)............	46

ABSTRACT

The Exo Powercam (PC) crank purportedly allows a cyclist to pedal a bicycle at a slower cadence and larger gear than the standard crank (SC) without sacrificing power output. If this were true, physiologic responses in oxygen consumption and heart rate should decrease and/or performance should increase.

A two-part investigation was designed to test the performance of the PC against the SC. The first part, a series of three rides for each crank, tested whether performance had reached a steady state so that an accurate comparison could be made between crank mechanisms. Once a steady state was achieved, absolute oxygen uptake was compared between cranks for identical workloads.

The second part of the study measured performance between cranks in a time trial race. A transition to treadmill running immediately followed each time trial to simulate a triathlon switch from cycling to running.

The evaluation of the ride series showed no significant difference in rate of learning between the PC and the SC in either oxygen consumption ($P = 0.13$) or heart rate ($P = 0.49$). The absolute oxygen consumption of ride three demonstrated no significant difference between the cranks (mean oxygen uptake, SC = 2.27 l/min, PC = 2.26 l/min, $T = 0.3167$, $P = 0.76$).

Elapsed time for the time trial race was nearly identical between cranks (SC = 66.86 minutes, PC = 66.90 minutes, $T = -0.0421$, $P = 0.97$). Oxygen consumption, heart rate and relative perceived exertion also exhibited no significant difference at the $P < 0.05$ level, nor was the oxygen uptake for the treadmill runs significantly different. However, a subgroup of cyclists who were conditioned through running had faster elapsed time on the PC with less oxygen uptake (mean elapsed time, SC = 72.24 minutes, PC = 69.21 minutes; mean oxygen uptake, SC = 2.17 l/min, PC = 2.10 l/min).

While the PC did not exhibit improvement in the measured physiologic or performance parameters when compared to the SC, neither did it exhibit a decrease. However, runners did show improvement with the PC.

In light of its comparable performance to the SC, the PC deserves further study with more precise adjustments to the cam. Also, the PC should be tested with a larger group of runners.

CHAPTER 1

INTRODUCTION

The development of the bicycle has been marked by innovation throughout its history. Many of these innovations have centered around the crank mechanism. One inventor modified the traditional continuous circular pedal motion to a discontinuous circular motion that the inventor claims is a more efficient use of leg force (Brown, 1984). The mechanical device, the elliptical cam crank named Exo Powercam (PC), purportedly reduces muscle fatigue through a decrease in pedal frequency relative to workload and therefore fosters increased endurance (Brown, 1984). The inventor has also claimed that the discontinuous rotational pattern of the legs more closely duplicates the motion of running or walking which allows for a more efficient transition to running after bicycling in triathlon races. Little research has been conducted to test these claims. This investigation explored the physiological responses of cycling with the Powercam in comparison to cycling with the standard crank (SC).

Problem Statement

1. Is there a learning effect over a series of rides using the SC or the PC and does learning occur at the same rate for each crank?
2. Do cyclists exhibit differences in oxygen consumption when performing identical workloads using the PC as compared to the SC?
3. Is there an improvement in performance for time trials with the PC as compared to the SC?
4. Is there increased efficiency in shifting from cycling to running when using the PC as compared to the SC?

Hypothesis

No significant differences exist between the crank mechanisms in learning efficient pedalling technique, in exhibited physiological responses, in time trial performance, or in efficiency in shifting to running from cycling.

Limitations

1. Subjects were volunteers who lived in the Bozeman area during 1985-86 and whose leg length fit the restricted range of adjustments on the bicycle used for testing.
2. Eleven subjects, six male, five female, completed the testing for Phase I to determine if a learning effect exists. Eight subjects, four male and four female,

completed the testing for Phase II, a simulated time trial.

3. Subjects represented three classes of bicycling experience: competitive, recreational, and novice.

Delimitations

1. Cyclists selected one hand position on the handlebars which was used throughout testing for that subject.
2. A Windtamer bicycle frame mounted on a Road Machine brand of resistance machine provided the workload.
3. Workload was measured using a Cateye Solar Cyclocomputer.
4. One tester took all physiologic and anthropometric measurements.
5. The elliptical cam of the PC crank was tested with its reference mark at top dead center only.
6. Phase I consisted of a series of three rides at identical workloads completed within a one week period for each crank mechanism.
7. Phase II was preceded by six hours of practice on the Powercam crank per manufacturer's recommendation (Brown, 1986).

Definitions

Cadence - the rate of pedalling, measured in revolutions per minute of one foot, e.g. pedal frequency or pedalling rate (Borysewicz, 1985).

Exo Powercam crank - (manufactured by Houdaille Industries, Incorporated) a crank mechanism that uses a cam with a modified elliptical shape fixed to the frame, a linkage mechanism (the oscillator) which is pinned to the crank engaging the chainwheel at its toothed upper end and riding on the cam with a roller on its lower end (Figure 1).

Experience level of cyclists - (for this study) competitive cyclist - cyclists having competitive experience at the state level; novice cyclist - a cyclist who has learned to ride a bicycle but does not ride regularly; recreational cyclist - a cyclist who regularly rides a bicycle or who has touring experience but does not engage in bicycling competition.

Gear ratio - the combination of gear and wheel diameter which will move the bicycle forward a specific number of inches per crank cycle (Sloane, 1970). Gear ratio is calculated by multiplying the ratio of chainwheel teeth divided by freewheel teeth with the wheel diameter.

Leg force magnitude - the instantaneous magnitude of the force generated by the muscle of the leg in overcoming a resistance (Brown, 1984).

Phase I - the portion of this study designed to determine increased efficiency over a series of rides on each crank mechanism and differences in learning rates and

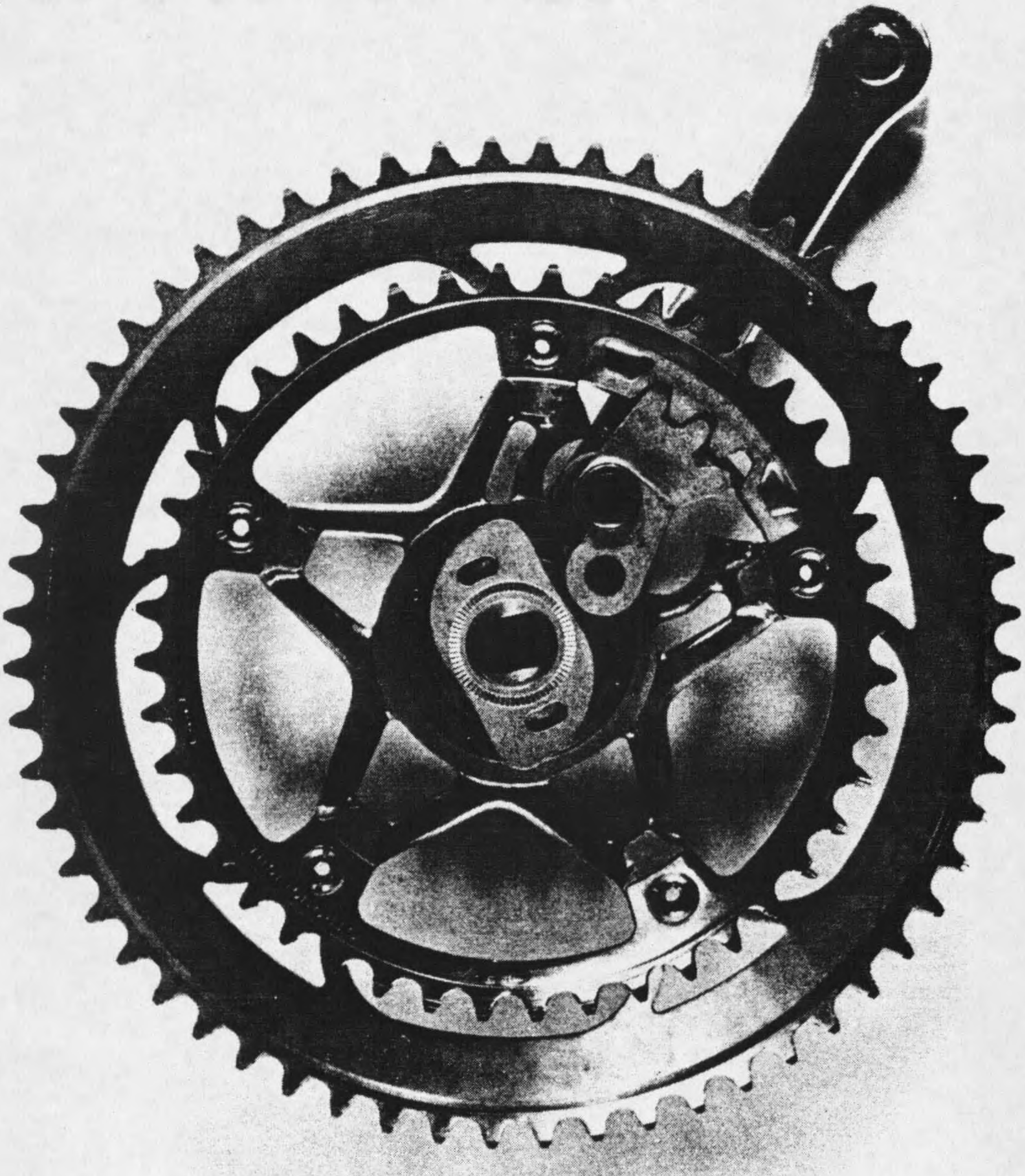

Figure 1. Exo Powercam crank designed and manufactured by Larry G. Brown.

performance between the cranks as measured by oxygen consumption and heart rate (HR).

<u>Phase II</u> - the portion of this study designed to test physiologic responses and performance elicited by each crank mechanism during a 40K time trial followed by a transition to running.

<u>Spinning</u> - maintaining a uniform rotational pedal speed through 360 degrees of the crank cycle (Brown, 1984).

<u>Standard crank</u> - conventional crank mechanism that consists of a circular chainring with a crank arm rigidly attached.

<u>Time trial</u> - a race against the clock (Borysewicz, 1985).

<u>Torque</u> - something that produces or tends to produce rotation or torsion and whose effectiveness is measured by the product of the force and the perpendicular distance from the line of action of the force to the axis of rotation (Webster, 1969).

CHAPTER 2

REVIEW OF RELATED LITERATURE

Development of the Exo Powercam

The Exo Powercam (PC) is one version of the original Facet Biocam which was the first marketable device of several prototypes designed by Larry G. Brown. The PC was developed by Brown, an MIT graduate in mechanical engineering, for the purpose of reducing leg stress during cycling (Brown, 1984). The intent of this invention was to reduce the peak leg force necessary to generate a given torque.

The PC, a two-ounce, metal alloy cam, attaches to the right-hand, bottom bracket of a bicycle. A crank is mounted on a spider bearing which allows the crank to move either forward or backward in relation to the chainwheel. The crank's movement in relation to the chainwheel is controlled by an oscillator that is tipped up or down as it rolls over the cam which is a modified ellipse (Figure 1). The overall effect of the mechanism is to retard the crank arm in relation to the chainwheel at the beginning of each work portion of the chainwheel's revolution, then to advance the crank arm in relation to the chainwheel throughout the work portion of the cycle. Brown describes the type of motion used to pedal this mechanism as a "push-rest-push" motion that mimics walking or running more than the conventional crank (Brown, 1983).

Brown (1984) lists three inefficiencies related to the conventional crank which other researchers have also noted (Banister, Jackson, 1967; Böning, Gönen, Maassen, 1984; Coast, Welch, 1985; Seabury, Adams, Ramey, 1977). First, due to the increased pedal resistance of higher work loads, a cyclist on the conventional crank bicycle uses higher revolutions per minute (rpm) to optimize performance for higher work outputs. However, researchers have shown that more energy is expended in rotating the feet and legs rapidly as required by the higher rpms (Hagberg, Mullin, Giese, Spitznagel, 1981; Seabury et al., 1977). To address this inefficiency, Brown has designed the PC to allow a slower rpm at higher workloads while maintaining reduced pedal resistance.

Secondly, Brown contends the characteristic uniform rotational speed of the standard crank (SC), and, therefore, foot, is not a natural human motion. Walking or running motions have more clearly defined push-rest stages of each gait cycle of the foot. The "rest" portion of running would come at heel strike and continue through the stance phase of the stride; the "push" portion of the cycle would be from the stance phase through toe off. The PC does have clearly defined work-rest portions of the pedal cycle with the rest portion prolonged as compared to the standard crank (Wohlin, unpublished study, 1987).

Third, the inefficiency of the conventional crank is seen in the analysis of force vectors through the crank cycle (Brown, 1984). Force is most efficient when applied at a 90 degree angle to the rotating crank. With the flexibility of the ankle helping to position the foot and pedal in a more optimal vector, the effective range of the work portion of the pedal cycle is between 25-135 degrees from top dead center (Patterson, Pearson, Fisher, 1983). With higher revolutions per minute, a larger portion of the force is still being applied to the crank while the crank is not in a position to translate that force into torque. At higher pedalling rates, the muscle cannot contract fast enough to finish applying force precisely at 135 degrees. Tension remains on the crank past 135 degrees and often through 180-185 degrees. The result is tension on the crank arm, with little of the force contributing to torque and a portion even opposing the next work portion of the cycle (Patterson et al., 1983).

Brown contends that the PC overcomes these three inefficiencies by reducing the amount of torque needed to overcome the specific pedal resistance at any given workload (Brown, 1984). If Brown's hypothesis is correct, the specific pedal resistance for a workload would be reduced by the PC crank mechanism, and therefore, the cyclist would be able to reduce rpm. The specific pedal resistance at a slower rpm would then approximate that found at a higher rpm with a SC. Thus the most efficient pedalling rate for a given work output using a PC would be slower than that of a conventional crank, yet pedal resistance would remain the same or decrease. Physiologic improvement should come from the reduced work of the muscles used to move the leg and stabilize the body which causes inefficiency at high rpm. Lower peak leg force magnitude should also delay fatigue of the leg muscles due to decreases in muscle fiber recruitment and should enhance endurance.

Several world class cyclists have trained and raced on the PC. They recommend the PC for distance rides and low rolling hills and commented on the relative lack of fatigue they felt at the end of sustained rides (PC advertisement in Bicycle magazine, Sept-Oct 1984). The PC has also received endorsement from the Association of Professional Triathletes and the National Triathlon Training Camps.

The unique motion of the PC with distinctive push-rest portions of each foot revolution has been claimed to more closely resemble the motion used in running or walking. Triathletes have been named as one group that would benefit most from this distinctive foot motion because more of their training could be done on the bicycle and less from running (Brown, 1984). Conversely, athletes who run for their training could have a greater efficiency on the PC because of the similarity of motion between the two. Neither of these claims has been tested.

Theoretical Validity of Claims

Cadence

The advantage of the PC is that it may allow a lower pedalling cadence at any given workload without the normally large increase in pedal resistance per revolution. This mechanical advantage could then translate into a physiologic advantage, lower energy cost.

Cycling at 40-60 rpm has been shown to be the most efficient cadence physiologically by many researchers (Garry, Wishart, 1931; Banister, Jackson, 1967; Hagberg et al., 1981; Coast, 1985; Coast, Cox, Welch, 1986).

The study conducted by J.M. Hagberg, J.P. Mullin, M.D. Giese, and E. Spitznagel tested the effect of pedal frequency on the physiologic responses of seven competitive cyclists. The cyclists completed a progressive maximal oxygen uptake test cycling at 20 mph on their racing bicycles on a treadmill whose grade was raised by 0.5% each minute until exhaustion. Five five-minute work bouts followed at a workload set to elicit approximately 80% of their maximal oxygen uptake. Subjects completed the first ride in the gear that had been preselected by each individual as being their optimal performance gear. Subsequent rides varied in gear ratio enough to elicit two pedal frequencies above and two pedal frequencies below this pedal frequency. The speed of the treadmill was 20 mph and the rpms of 50, 75, 90, 105 and 120 were completed in a random order for each subject. The workload actually elicited an average oxygen uptake of 81.5% of maximum with a range of 74% to 89%. However, the varying pedalling rates, half above the preferred pedalling rate and half below, for the same absolute work output, elicited responses ranging from 74 to 100% of maximal oxygen uptake. A graph of the quadratic regression equation for these data revealed that the physiologic responses increased with either an increase or decrease in pedalling rates from an optimum rate. Two subjects improved oxygen uptake at a pedal frequency other than the one preferred.

The seven elite cyclists possessed optimum pedalling rates for the tested workload in a range from 72 to 102 rpm, with the average being 91 rpm. This average closely matches that used by competitive cyclists in racing situations.

The second portion of the study tested the cyclists for cost of limb movement only. This was accomplished by having the cyclists pedal their racing bicycles with the chain off for a five minute work bout, called an unloaded test. The cyclists pedalled at 60, 75, 90, 105, and 120 rpm. For the unloaded test, oxygen consumption, expiratory volume and heart rate all increased significantly as rpm increased; oxygen consumption and expiratory volume increased exponentially and HR increased linearly. These findings support the hypothesis that increasing the rpm for a given cycling output will require a greater effort physiologically substantiating the assumption that faster pedal rates are less efficient than slower pedal rates for a given workload. However, trained cyclists consistently choose higher rpms as workload increases to optimize performance as the first part of Hagberg's study revealed.

Other researchers have confirmed that an optimal pedalling rate exists for each workload and the optimum pedalling rate increases as the workload increases (Coast et al., 1985; Seabury et al., 1977). Seabury et al. (1977) tested three men at four work outputs using eight pedalling frequencies ranging from 30-120 rpm. Gross energy expenditure was calculated from measured oxygen uptake and respiratory quotient. Each power output elicited a unique optimal pedalling rate with the optimum rate increasing from 42 rpm at 40.8 W to 62 rpm at 326.8 W. Energy expenditure increases were more pronounced for slower than optimal pedalling rates when the power output was high and were more pronounced for faster than optimal pedalling rates when the power output was low. In these findings, the general principle that optimal pedalling rates increase as work output increases can assist competitive cyclists in choosing a rate that will be most efficient for the cyclist physiologically with energy savings as much as 5-10% of total expenditures (Kaneko, Yamazaki, Toyooka, 1979).

Coast and Welch (1985) tested five competitive cyclists using progressive maximal workloads on an ergometer. Each rode at pedalling rates of 40, 60, 80, 100 and 120 rpm at workloads of 100, 150, 200, 250 and 300 W. Oxygen consumption and heart rate were measured for each test then plotted according to pedalling rate for each workload. Significant variance existed among oxygen uptake and HR values for the same work output but differing pedalling rates. The results, when plotted, followed a parabolic curve with the lowest point on the curve representing the optimum pedalling rate for that workload. A linear progression of optimum pedalling rates was seen as workload increased, indicating that efficiency is enhanced when a faster cadence is used at greater workloads.

Pedal Resistance

Slower pedalling rates for a specific power output increase pedal resistance. R.P. Patterson and J.L. Pearson measured the total resultant force exerted by a cyclist on the pedals at varying pedalling rates. Eight male subjects rode for six minutes on two separate occasions at 40, 50, 60, 70, 80 and 90 rpm using workloads that represented 30 and 60% of their maximal oxygen uptake. Force plate pedals were used to measure the forces applied to the crank. Total force was greatest at 40 rpm and least at 90 rpm. But the force effectiveness index, calculated as the average of total force divided by the average force over one crank cycle, was less for 90 rpm than for 40 or 60 rpm.

This decrease in efficiency reflected the decrease in optimally directed forces in relation to the pedals at increased pedalling rates. At 90 rpm, 66% of peak leg force magnitude was still being exerted on the crank when it reached 180 degrees from top dead center (TDC). This force produces no work but is dissipated as tension on the crank arm, or if prolonged beyond 180 degrees from TDC, opposes rotation. The opposite leg must produce enough torque to overcome this negative resistance and still provide enough positive torque to maintain a constant pedalling speed. Therefore, an upper limit to rpm exists at which the misdirected forces cause the positive torque requirements to increase to the same levels as much slower rpms, so the usual benefit of reduced pedal resistance is not realized.

One explanation of this phenomenon was posed by Patterson (1983). He reasoned that at higher rpm the inability of the muscles to contract in the shorter amount of time that the crank is in an optimal position causes the forces to continue longer in the crank cycle than desired.

Blood Flow

Rhythmic contraction of the muscles such as that of cycling or running can increase local blood flow (Tønnesen, 1964; Folkow et al., 1970). B. Folkow, P. Gaskel and B.A.

Waaler studied venous blood flow in intact and isolated cat calf muscle that was induced to rhythmic activity. Optimal venous pressure lowering occurred with a stimulus frequencies of 40-60/min and with stimulus trains lasting for 200-300 msec. With the limb inferior to the heart, blood flow in the rhythmically contracting limb increased 46% above blood flow in the post-exercised, stationary limb. The contracting muscles exert pressure on the veins causing increased venous output during the contraction with an attending decrease in venous pressure. Between contractions, blood flow into the muscle was maximal because of this decreased resistance in the veins and thus an overall increase in perfusion.

Of critical importance to this increase in blood flow in exercising muscle is the relative duration of contraction and inter-contraction periods. Venous pressure must be lowered enough during the contraction portion of the rhythmic exercise to allow the venous pressure to remain decreased for a portion of the inter-contraction period. With contractions lasting from 0.2-0.3 sec and being repeated once per second, the venous compartment had enough capacity to receive a large influx of blood for about 0.5-0.7 sec. without developing a significant increase in local venous pressure.

K.H. Tønnesen's (1964) research has also supported the finding that blood flow will increase in exercising muscles. But his findings can be interpreted to state that an upper limit in work intensity exists above which blood flow will no longer increase. Nine male subjects lifted weights attached to their foot after having 133 Xenon injected into the lateral head of the gastrocnemius muscle. A scintillation crystal detector was placed 15 cm below the injection site and connected to a pulse analyzer and recording mechanism. The rate of 133 Xenon clearance was thus measured and muscle blood flow calculated. Muscle blood flow increased proportionately in exercising muscle up to approximately one-half possible maximal exertion for that muscle. Above this point, muscle blood flow no longer increased, indicating that an upper limit in blood flow through muscle exists. The capacity of the blood vessels was probably the limiting factor. Blood flow after cessation of the exercise never exceeded blood flow rates during exercise and fell smoothly to resting levels as soon as exercise stopped.

Blood flow through exercising muscle will greatly influence lactate accumulation. Studies of lactate production and clearance show that lactate production is affected by glycogen stores, intensity and duration of exercise, and muscle fiber type (Rodbard, Pragay, 1968; Göllnick, Bayly, Hodgson, 1986; Hermansen, Stensvold, 1972; Brooks, 1986; Donovan, et al., 1983). Clearance of lactate depends on several factors, also, such as blood flow through the working muscle, initial lactate level, muscle fiber type, level of training, and glycogen stores. Of these factors affecting production and removal of lactate, blood flow through muscle can be altered by differences in rpm. Slower cranking speeds require a greater maximum leg force or muscle tension and for a longer period of contraction than faster rpms. This may occlude the arteries for longer than optimum and allow venous refilling to continue longer than optimum, thereby preventing a maximal blood flow through the working muscle. Conversely, a muscle contraction may be too brief to lower venous pressure enough to allow optimal refilling or of insufficient magnitude to act as an auxiliary pump.

Reduced blood flow has been shown to lengthen the time of metabolite removal from working muscle (Rodbard, Pragay, 1968). Accumulation of metabolites rapidly impedes the ability of the muscle to contract. Therefore, an optimum contraction duration such as cycling at 60-70 rpm could improve lactate removal.

Relative Perceived Exertion (RPE)

Perceived exertion dictates what rpm is chosen by cyclists at any given workload. Borg (1973) compared four methods of rating perceived exertion and correlated each to HR. HR and perceived exertion were recorded every second minute during two work tests. Correlation coefficients were calculated between ratings and heart rates by sampling scores from varying time intervals. The correlation coefficients were similar for all rating methods used. Each method of rating was equally accurate in representing perceived exertion in accordance with HR, therefore, there must exist a fundamental relationship between the physiological indicators of stress such as HR and the psychological perception of exertion.

In general, as HR increases, exertion is perceived as harder. However, this relationship has exceptions due to another physiologic factor affecting perceived exertion. Pandolf and Noble (1973) tested fifteen trained male cyclists on an ergometer at various pedalling speeds and workloads. The pedalling frequencies ranged from 40 to 80 rpm while the power outputs ranged from 550-1075 kgm/min. Oxygen uptake, used to measure the energy cost for the differing pedalling speeds at equivalent power outputs, did not differ significantly. RPE responses at equivalent power outputs were significantly elevated at the lower pedalling frequencies and higher power outputs. Because HR was the lowest at 40 rpm and oxygen uptake unchanged, the elevated RPE ratings for this rpm cannot depend on HR alone. The greater torque needed to overcome the greater resistance in slower cadences results in greater muscle and joint tension. Proprioceptive muscle and tendon sensations monitor the contractile lengths of muscle and the amount of tension on the muscle and tendons. This experiment can be interpreted to mean that the proprioceptive sensations provide another physiologic indicator of stress that can elevate psychological perception of exertion.

Seabury et al. (1977) suggests that the most efficient pedalling rate is a balance between two forces: (1) total load on each contracting muscle fiber per cycle and (2) the total number of contracting fibers engaged per cycle. The balance between these forces will be unique to an individual depending on muscle fiber type and conditioning. The author suggested that with training, athletes can improve their muscle twitch reflexes, and thus are able to maintain a higher rpm which favors reduced fiber recruitment and a reduced load per fiber.

Hubert Löllgen, T. Graham, and G. Sjolgaard (1980) studied the effects of central and peripheral factors on perceived exertion. Six males exercised at zero, submaximal and maximal loads on a bicycle ergometer at pedal rates from 40-100 rpm. Central factors of HR, oxygen consumption and ventilatory volume were recorded and correlated to RPE. Peripheral factors of muscle tension and muscle metabolites were also measured and correlated to RPE. While many physiologic and proprioceptive measures demonstrated significant variance at differing pedal rates and constant workload, RPE did not vary significantly. None of the central nor peripheral factors alone influenced RPE significantly. Therefore, RPE must be derived from a complex interaction of many variables. Two factors, namely leg force magnitude and rpm did approximate changes in RPE but the correlation was nonsignificant.

Another study demonstrated that the additional physiologic cost of moving the limbs at a higher rate may not be of sufficient magnitude to negate the benefit of reduced load on muscle fibers. Kaneko et al. (1979) measured the internal work of the muscle and joints involved in pedalling. Four male subjects pedalled a Monark cycle ergometer with and without load (0, 1, 2, 3, 4, and 5 kp) at a constant frequency of 50 rpm. Leg movement was recorded on film at 64 frames per second, and kinetic energy was calculated at approximately 30 millisecond intervals by Fenn's procedure (Fenn, 1930). The sum of the kinetic increments for thighs and lower legs was considered as internal work. External work and oxygen uptake were measured in a conventional way and efficiency was then calculated using three standard formulas and one the authors proposed to include adjustments for internal work. All methods resulted in similar findings for efficiency and did not differ significantly.

The lack of difference between the conventional methods of determining efficiency and the authors adjusted method was due to the relatively small proportion of total work that was made up by the internal work of moving the limbs. Internal work did not vary significantly between 0 to 3 kp but increased appreciably at higher loads. However, when comparing internal work to external work, the internal work for lower power outputs (<1 kp) represents 20-30% of the total work done. At the higher power outputs, the absolute amount of internal work was increased, but it constituted only 5-10% of external work and may explain why competitive cyclists prefer higher rpm at greater work output; the extra effort of moving the legs quickly is not sufficiently stressful to negate the benefit of reduced strain on muscles and tendons.

Application of Theories

Human exercise utilizing machines has a complex interaction of physiology and biomechanics. Physiologic factors such as oxygen consumption, HR, blood flow and lactate levels are affected by the mechanical factors that determine muscle fiber recruitment, load per muscle fiber, and the rate of limb motion (cadence). For cycling, when muscle fiber recruitment increases, allowing more work to be done per revolution of the crank and thus allowing decreases in cadence at a specific workload, the perception of exertion increases. Endurance also decreases as muscle fiber recruitment increases because the muscle has fewer reserve fibers to power contractions once fatigue overcomes the initially recruited fibers. Yet faster cadences require a greater physiologic cost due to the increased motion of the limb; muscles must contract faster and more frequently to pedal more quickly. Balancing the contribution of each factor in maintaining a given workload is the key to maximizing performance in cycling. The PC attempts to balance these variables to produce a more efficient match-up between human and cycle.

Specifically, Brown claims that the PC fitted bicycle will allow greater performance in road races of more than an hour's duration, such as the Race Across America, or in triathlons where the movement pattern of the PC more closely mimics that of running. The triathlete could benefit from this by faster transition times from cycling to running and by allowing less conditioning through running and more through cycling.

While the theoretical basis exists for these claims, whether the Powercam can deliver significant modification to the biomechanical factors to show an improvement in the physiologic responses had not been addressed. This study was designed to test whether the Powercam did provide a physiological advantage when cycling at a given workload or a performance advantage when time trial racing. Also, the amount of cycling needed to become efficient with the distinctive motion of the PC was measured.

CHAPTER 3

METHODS

The research design used was a test-retest with each subject acting as his/her own control. A two part investigation was conducted comparing physiological performances between the standard crank (SC) and the Exo Powercam (PC). The first, Phase I, investigated the learning/increased efficiency for oxygen consumption and heart rate (HR) over a series of rides for each crank. The rate of learning for each crank was then compared to ascertain whether the improvement in efficiency had reached a plateau to permit an accurate comparison between cranks. After the increase in efficiency had taken place, the two cranks were compared for efficiency using the last ride of the series.

The second part of this investigation, Phase II, was a simulated time trial for a set distance of 40K. Subjects were measured for elapsed time, oxygen uptake, HR and relative perceived exertion (RPE) for each performance. At the end of the time trial for each crank mechanism, a treadmill run to simulate a transition from cycling to running during a triathlon was completed with oxygen consumption measured.

Subjects

Eleven subjects completed Phase I testing; eight subjects completed Phase II testing. The experience level of the subjects ranged from competitive cyclists to novice. The subjects were volunteers who possessed leg length between 32-36 inches to allow for proper seat adjustment on the bicycle frame. None of the subjects smoked and all had physical examinations prior to the start of testing. Subjects were briefed on all test protocols prior to the start of the test and signed a consent form approved by the Human Subjects in Research committee of Montana State University (Appendix A). Subject characteristics were collected using a questionnaire (Appendix A) and height and weight measurements were taken at the beginning of the test; a summary of subject data is found in Tables 1 and 2.

Equipment

Bicycle

The bicycle frame was a 23" Windtamer manufactured by Houdaille, USA, producers of the PC, and was mounted on a Road Machine wind trainer, also manufactured by Houdaille, USA. The wind trainer utilized a 17-pound airbraked flywheel to obtain a pedal resistance and momentum that closely resembles actual bicycling. Gearing for the bicycle used a double front chain ring with a tooth ratio of 44/52 for the

Table 1. Characteristics of subjects for Phase I testing.

Sub/Experience*		Gender	Age (yrs)	Ht (cm)	Wt (kg)
KS	Nov	F	37	179.5	68.2
SR	Nov	M	24	183.0	83.6
FC	Nov	M	46	184.3	76.8
LJ	Rec	F	21	174.1	56.4
PF	Rec	M	34	176.6	78.6
MT	Rec	F	19	175.6	60.5
WG	Com	M	40	184.3	75.0
ST	Com	F	27	169.0	55.5
SH	Com	F	22	176.6	63.6
BG	Com	M	35	171.5	68.6
TG	Com	M	38	181.8	72.7
MEANS			31.3 ± 9.2	176.5 ± 5.2	68.8 ± 9.2

*Experience level: nov-novice, rec-recreational, com-competitive.

Table 2. Characteristics of subjects for Phase II testing.

Sub/Experience		Gender	Age (yrs)	Ht (cm)	Wt (kg)
KS	Nov	F	37	179.5	68.2
DB	Rec	M	34	189.4	70.5
LJ	Rec	F	21	174.1	56.4
PF	Rec	M	34	176.6	78.6
MT	Rec	F	19	175.6	60.5
WG	Com	M	40	184.3	75.0
SH	Com	F	22	176.6	63.6
TG	Com	M	38	181.8	72.7
MEANS			30.8 ± 8.6	178.3 ± 5.5	68.0 ± 7.3

SC and 44/60 for the PC crank and a rear sprocket with a seven ring combination of 12/13/14/16/18/28/32 teeth respectively. The crank arms were 172.5 mm in length for both the SC and PC. The work output was measured in miles per hour (mph) for Phase I and kilometers per hour (kmph) for Phase II with a Cateye Solar Cyclocomputer, model CC-2000.

Gas Analysis

Expired air was collected in a 350-liter Tissot tank then analyzed using a Beckman E-2 Oxygen analyzer and Beckman LB-2 carbon dioxide analyzer. Both analyzers were pre-calibrated using known concentrations of gases prior to each test. Expired gases were collected for one minute periods (Appendix B) and concentrations calculated using standard gas analysis procedures (Appendix B).

Heart Rate

Heart rate (HR) was recorded with a Sears Pulsemeter attached to the ear or by carotid palpation. The HR was taken at the same time expired gas was being collected.

Treadmill

A Pacer R-90 treadmill was used for the running measurements in Phase II. The treadmill was set at 0 degrees elevation and the speed set to the normal running pace of the subject.

Procedures for Phase I

Pilot Test to Determine Workload

Subjects were given a 20-minute submaximal practice ride using the SC. The speed was unique to each subject and reflected a HR close to 80% of the subject's age-adjusted maximal HR. Height, slope and forward placement of the seat was adjusted to allow full extension of the leg. Full leg extension was chosen over lesser seat heights because this more closely matched recommendations for the PC while still being efficient for the SC and was easier to establish. These parameters were recorded and preserved for each ride of both series (SC and PC) to preserve standardization. The workload was measured by a Cateye Solar Cyclocomputer in mph. Once the speed was selected, it became standard for all rides completed on both crank mechanisms.

The PC ride series was completed in a larger gear ratio and slower cadence than the SC series while maintaining the preselected speed. Gear ratio for the ride series on each crank was self selected by the subject and sometimes reflected the subject's inexperience. The one subject who had a slower cadence on the SC than the PC had nearly identical gear ratios for the two cranks (SC = 100.29 inches, PC = 101.25 inches). Cadence could vary two to three rpm to maintain speed in mph; this subject's cadence for the SC was 68.3 and was 69.4 for the PC. To further control variance in cadence as it relates to speed, all other testing was done in kmph which had only a one to two rpm variance to maintain speed. The gear ratios selected by the subjects for the SC and PC are summarized in Table 3.

Table 3. Gear ratio (GR) and mean cadence used by each subject for each crank.

		Cadence in RPM		GR in Inches	
Subject	Experience	SC	PC	SC	PC
KS	Nov	78.6	67.5	87.75	101.25
SR	Nov	74.9	64.5	100.29	115.71
FC	Nov	81.9	62.7	87.75	115.71
LJ	Rec	83.6	61.6	66.00	90.00
PF	Rec	68.3	69.4	100.29	101.25
MT	Rec	72.5	62.3	100.29	115.71
WG	Com	89.6	68.0	87.75	115.71
ST	Com	93.9	69.4	66.00	90.00
SH	Com	90.3	80.6	66.00	74.25
BG	Com	78.3	67.7	100.29	115.71
TG	Com	90.6	77.9	87.75	101.25
MEAN		82.0	68.3	85.20	102.41

Test Protocol, Phase I

Two series of three rides each were completed; the first series was completed on the SC, the second on the PC. Once either series began, it was completed within a week to minimize the effects of conditioning. Caffeine and food intake were restricted two hours before each testing session. A five minute warm-up preceded each 30-minute ride. Cadence, gear ratio and speed were held constant throughout the three rides of each series, but cadence and gear ratio were reset for the PC series as described. Expired gases and HR were measured at minutes 6, 12, 18, 24, and 30. A summary of procedures is contained in Appendix B.

Statistical Design for Phase I

An adaptation of a randomized block factorial ANOVA for repeated measures and Scheffe's multiple comparison test were used to compare differences between rides within a series and to assess ride and crank interaction. General Linear Models 6.03 IBM/PC by Phil Spector, James H. Goodnight, John P. Sall and Warren S. Sarle and the SAS STAT Guide by the SAS Institute, Incorporated were used for these analyses. Paired t analysis was used to evaluate differences in absolute oxygen consumption between cranks. The paired t analysis employed Dr. Richard E. Lund's MSUSTAT.

Procedures for Phase II

Pilot Test

A submaximal 30-40K ride on the PC with a treadmill run following the cycling was completed to select a treadmill pace that the subject felt he or she could maintain for five minutes following a maximum effort on a time trial. Prior to the ride the appropriate treadmill pace was practiced. Also, three additional hours of practice were completed on the PC to allow each subject the minimum practice recommended by the manufacturer to learn the distinctive pedalling motion for the PC. Seat height, slant and forward positioning over the pedal were adjusted during the practice rides until the subject felt most comfortable; both 40K rides were completed from this position. Each subject was also acquainted with Borg's RPE scale.

Workload

The simulated time trial distance was set at 40K with subjects free to use any gear ratio/cadence combination during the ride. Speed was not held constant. Elapsed time was the measure of performance.

Test Protocol, Phase II

The order in which each crank mechanism was tested was randomized. During each time trial, expired gases and HR were measured at Km 9, 18, 27, and 36 for a one minute sampling. RPE, using Borg's RPE scale, was measured at Km 9, 18, 27, and 35. The two time trials were completed within a two week period for each subject.

Following cycling, the subject ran for five minutes at his/her preselected speed on the treadmill. Expired gases were sampled during the first minute and last minute of the five minute run. These samples were averaged to give a mean oxygen uptake used to compare the two cranks. Average time lapse between the cessation of cycling and the start of running was three minutes to allow changing of footgear. A summary of procedures for the time trial test is found in Appendix B.

Statistical Design for Phase II

Dr. Richard E. Lund's MSUSTAT paired t with correlations was used to analyze differences in elapsed time, oxygen consumption, HR and RPE for time trial performance and oxygen consumption for the treadmill run.

CHAPTER 4

RESULTS

Introduction

Two independent tests were conducted to test the effectiveness of the Exo Powercam (PC) as compared to the standard crank (SC). The first test, Phase I, compared differences in acquiring efficiency, defined as decreasing heart rate (HR) and oxygen consumption among rides in a series that used the same workload. This efficiency change within the series was then compared between the two cranks to determine whether efficiency on both cranks had reached a stable value. Phase I also compared absolute differences in oxygen consumption between cranks at the last ride in the series.

Phase II tested performance as measured by elapsed time, HR, oxygen consumption and relative perceived exertion (RPE) for a 40K time trial. A treadmill run immediately following each 40K time trial was used to test efficiency in switching from cycling to running as is done in triathlon competition.

Phase I, Learning Curve

Oxygen Consumption

In Phase I, the subjects completed three rides on the SC and three more rides on the PC at identical workloads. The workload was provided by two wind resistance machines. The machines were not significantly different in efficiency, but an absolute difference was noted with the resistance device used for the PC requiring less oxygen consumption for identical workloads. This difference, 0.13 l/min, was factored into all calculations for oxygen consumption. It was not possible to use the same wind resistance device because of mounting problems with the PC.

Table 4 contains mean values for oxygen consumption for each ride and is presented in Figure 2. The difference in oxygen consumption between rides regardless of crank was analyzed first using an adaptation of a randomized block factorial ANOVA (ANOVA F). This comparison was used to determine whether any difference existed in oxygen uptake between the rides, i.e. ride one from both cranks against ride two from both cranks and so on. The F-ratio was 10.5828 with a probability (P) of significant difference acceptable at the 95% level (P = 0.0007).

Because a significant difference did exist between rides, further analysis was necessary to determine where these differences occurred in the ride series for each crank.

Table 4. Mean oxygen consumption (± SE) for each ride for each crank.

	SC		PC	
Ride #	Mean l/min	± SE l/min	Mean l/min	± SE l/min
1	2.371	.1576	2.305	.1325
2	2.287	.1656	2.299	.1340
3	2.270	.1605	2.258	.1351

ANOVA F and Scheffe's multiple comparison were used to analyze each crank separately for differences between rides. The ANOVA F test showed a significant difference between rides in the series for the SC (F = 7.9586; DF = 2, 20; P = 0.0029). The Scheffe's test, which indicates which values are significantly different from the other values, identified oxygen uptake for ride one to be the significantly greater value ($P < 0.05$). Figure 2 illustrates this improvement in oxygen consumption between rides one and two. However, rides two to three were not significantly different for oxygen consumption.

The examination of oxygen consumption for the PC ride series using the same two analyses, showed no significant decrease in oxygen uptake between any rides (ANOVA F, F = 2.5086, DF = 2, 20; P = 0.1066). A fourth and fifth ride were completed by six subjects to determine whether oxygen uptake would decrease at a later point in the series, but oxygen uptake values did not improve over ride three values and in