POWER DEVELOPMENT IN HILL CLIMBING

AS A FUNCTION OF BICYCLE WEIGHT

Submitted by

Brandon M. Wood

A Thesis submitted in Partial

Fulfillment of the Requirements for

The Master of Science Degree

Thesis Chair: Dr. Steven J. Albrechtsen

THE UNIVERSITY OF WISCONSIN-WHITEWATER

January 25, 2007

The University of Wisconsin-Whitewater

Thesis Approved

Brandon M. Wood

Date: January 25, 2007

Committee Members: ______________________________

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ACKNOWLEDGEMENTS AND DEDICATION

This thesis could not have been done without:

God, for guiding me through both smooth and rough waters

My Mother, for her spiritual wisdom and undying love

My Father, for getting me involved with cycling

Amanda Chladek, for her unconditional love and support

The people at the Trek Store, for your bicycle knowledge and friendship

The amazing people at Saris, for all of your wonderful help and guidance

All of my friends and family, for making my life so special

Dr. Steven J. Albrechtsen, for all of your wisdom

Steve Brown, for helping me to realize my academic passions

Meagan Cook, for your guidance in writing this thesis

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Brandon M. Wood

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January 25, 2007

Dr. Steven J. Albrechtsen, Thesis Chair

The University of Wisconsin-Whitewater

ABSTRACT OF THESIS

POWER DEVELOPMENT IN HILL CLIMBING

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The purpose of this research was to evaluate the effects of differences in the weight of bicycles on power development while riding uphill. Thirteen competitive bicycle racers performed two hill climbs in a single exercise session up a 1.78 mile hill on which they have previously trained. During both hill climbs the subjects rode their own bicycles which were previously fitted with a Saris Cycling Group PowerTap SL 2.4 power meter on the rear wheel of the bicycle. During one climb 1.0 kg of sand was added to a water bottle on the bike frame to determine the difference in wattage per gram of weight added to the bike. The order in which the bikes were weighted was randomized to keep the riders from knowing if they had the bottle filled with 1.0 kg of sand or if they had the one that was empty. The subjects were allowed 30 minutes to recover following the first hill climb before starting the next one.

The maximum wattage output with 1.0 kg weight added to the bicycle was consistent among all of the test subjects except two, with an average increase of 53.77 watts being produced. Another factor that was constant among all of the subjects except one was an increase in the amount of time it took them to reach the summit of the climb with the 1.0 kg weight added to their bicycle. The average amount of extra time was 21 seconds. The average power output for the entire group of test subjects with the 1.0 kg weight added to their bicycle during the hill climb was -3.462 watts. The results showed

that when weight is added onto a cyclist or their bicycle, the effort (power measured in watts) at which they need to maintain the same speed they are able to travel with a lighter bicycle is significantly increased.

This type of information is important to those who would like to know how they can ride their bicycle to the summit of a climb faster than before. Those who might have particular interest in these types of results would be the athletes who compete in bicycle racing. The numerous materials that are used in today's manufacturing of bicycle frames and components allow cyclists to measure each gram of weight that they either put onto or take off of their bicycle. Knowing just how much time and energy they are saving or losing from those grams helps the athlete when it comes to both training and racing.

CHAPTER I

INTRODUCTION

Power to Weight Ratio

In cycling, those who have a greater power to weight ratio generally are the ones who are able to ride uphill the fastest. Power is the rate of doing work (P = force x distance/time) and the product of force and speed (P = force x velocity). In both instances, power is measured in watts (W). Power can be calculated as an average, a maximal number/peak number, or both. The power to weight ratio is then improved by increasing one's overall wattage output, or decreasing the weight one carries on their bicycle while producing the same amount of wattage. This study focused on the second of these two options for improving power to weight ratio.

History of Power and Bicycle Manufacturing

Since the mountains were first introduced into major races such as the Tour de France in the early 20th century, riders have been looking for ways to ride uphill faster. The mountains have always been where the overall race is decided for the main contenders and it did not take long for them to discover that the lighter riders were usually the best climbers. To reduce one's weight on the bike without the individual actually losing weight (which can result in a loss of power as well), the only option is to reduce the weight of the bike itself. Because of this, manufacturers of bicycle frames and components the world over are constantly looking for ways to make their bikes as light as possible. This has caused bicycle manufacturing to become a billion dollar industry; one in which manufacturers are constantly searching for the newest and lightest materials available to make their bicycles.

Bicycle Manufacturing Materials

The first bicycles used in major competitions were made of welded steel and, by today's standards, are considered to be extremely heavy. With the numerous advances in technology over the years, new materials and methods of making bicycle frames were developed to make bicycles weigh about one-quarter of what they did a century ago. These new materials include: extremely light aluminum (scandium or zirconium), titanium, and carbon fiber. While both aluminum and titanium can get extremely light, it was the development of carbon fiber materials that has had the greatest impact on the bicycle manufacturing industry in regard to weight.

The benefits of carbon fiber come from the fact that it is extremely light, offers a good amount of stiffness for optimal power transfer, and is compliant when going over bumps resulting in less rider fatigue. It also can be formed into almost any shape allowing for bicycles that are not only very light in weight, but also very aerodynamic in their configuration. It is because of all of these reasons that carbon fiber has become the material of choice so far in the 21st century when it comes to making high-end bicycles.

While titanium bicycles can be made extremely light, they do not have the ability to be as stiff as a carbon fiber bicycle. This plays a huge role in the materials a company chooses for their high-end bicycles. Being a powerful rider is one thing, but having a bicycle that allows you to transfer all of that power down into the road is quite another. The most powerful riders in the world could lose to less able competition if their bicycle flexed too much at the bottom bracket every time they pushed down on the pedals. This is why the bicycle companies that cater to the professional peloton choose to use carbon fiber in making their high-end bicycles.

Due to advances in the carbon fiber making process itself, multiple levels of quality have emerged. Most of the very high end bicycles that are manufactured today use the highest modulus carbon fiber sheets that the bicycle company obtains. The higher the modulus the carbon fiber is, the lighter the sheet is that is used in producing the bicycle. Cost is always another big issue in the development of bicycles as well, and the better the carbon fiber the more expensive the sheet is going to be. This forces many manufacturers to mix and match certain levels of carbon fiber until they obtain the bicycle with the best ride characteristics at the lowest price point.

As a bicycle’s weight gets lighter and lighter, the cost of that same bicycle also gets higher and higher. While it is relatively inexpensive to go from a bicycle that weighs twenty pounds to a bicycle that weighs sixteen, it is very expensive to go from a bicycle that weighs sixteen pounds to one that only weighs fifteen. This is because each gram of weight that is stripped off of a bicycle that is already considered to be very light has to be done using more technologically advanced materials and developmental methods. This means that the materials are both harder to find and harder to work with. This forces consumers to pay a very large sum of money so that they can gain seconds of an advantage over their opponents.

Development of Power Meters

With all of these new materials being used for bicycle building, a restriction of just less than 15 pounds was put on how light bikes could be in the professional peloton. This has driven many bicycle manufacturers to look more at other factors that can have a large impact on performance. The two that are most often researched are both aerodynamics and the bicycle's overall stiffness. The stiffness of the bicycle is being constantly scrutinized by manufacturers because it is what is needed for optimal power transfer. This examining of power transfer in bicycles has also led to the development of numerous power meters that measure a rider's wattage output when riding a bicycle. These can come in the form of a crankset, rear wheels, or stand alone units. The majority of these power meters use a strain gauge that flexes as the rider turns the cranks and therefore is able to measure torque. Once a torque measurement is taken the computer unit that comes with each power meter is able to calculate wattage output. This computer is mounted onto the handlebars so that the rider can have real-time data on how hard they are working, revolutionizing the way that cyclists are able to train.

A rear-wheel power meter called the PowerTap SL 2.4 developed by the Saris Group was used throughout this experiment. This particular unit was chosen for its accuracy of measurement (+/- 1.5%) and ease of use in regard to attaching it to multiple bicycles. This power meter has been proven to be both accurate and reliable in the professional peloton for many years.

Training and Performance Improvement with Power Meters

The development of power meters for cyclists has made training much more complicated and precise at the same time. Power meters allow a rider to download the data from their day's ride onto their computer and then analyze that information. This data includes everything from average and maximum speed, power, cadence, heart rate and time (if interval training); as well as shows the rider multiple graphs of the data during the ride. While this may be complicated at first, it is actually a very big benefit once learned. This is because it allows both the rider and coach to see exactly what is going on at specific points during a ride and allows them both to correct any inefficiency that may be present. Having data such as this also serves as a "measuring stick" from year to year so that a rider can keep track of their progress and make sure that they are at their athletic peak during the right part of the season. A final and very important aspect that a power meter helps a cyclist analyze with more depth is their caloric expenditure during a ride (measured in kilojoules). This allows a rider to alter their nutritional intake to increase, maintain, or decrease their body weight depending upon what they want to achieve. This is the final step in regards to power to weight ratio, and something that elite cyclists monitor on a daily basis.

Studies of Power Meters for Cyclists

There have been numerous articles developed on power training and cyclist's power outputs. Lim is considered by many to be an authority on the subject of power measurement and cyclists. He works in conjunction with the Saris Corporation and helped develop their numerous PowerTaps. Lim also spent several years training some of the top cyclists in the world, including recent Tour de France winner Floyd Landis. Lim published an article (9) on the basics of training with power and explained how a cyclist should interpret the numbers properly. In the article he described what the data a cyclists receives from a ride means, and how to apply it to the training sessions they engage in down the road.

A similar article was published by Coggan in which he also gave an introduction to power meters and the many benefits they can have on a cyclist's performance. He stated that the advantage of training and racing with a power meter was to make it easier to more precisely control the overall training load (4). Coggan explained the inherent advantages and disadvantages that are involved with other forms of workload monitoring such as perceived exertion and heart rate. He said that while these methods can be very good at times, they do not give the precise measurements in regard to the workload that the athlete's body is going through. A power meter, on the other hand, provides this exact measurement in wattage. This provides a way for a cyclist to compare the difficulty of one ride to another or one race to another.

A study of particular interest by Gardner involved the accuracy of measurement of both the SRM power meter (crank based) and the Saris PowerTap (used in this study). This study tested numerous subjects and through cross-examination of multiple power measurements was able to calculate the accuracy of measurement of the two power meters (8). The study found both systems to be very accurate, and the difference between the two as far as accuracy was very minimal. This allowed the researchers in this study to go forth with confidence that the numbers that they were receiving were as accurate as any available.

There have also been numerous books published regarding the proper way to go about power training for cyclists and the benefits to be obtained. In fact, almost any coaching manual or book that gets published today contains some information on the benefits of training with a power meter. This is because when it comes to training, it benefits both the cyclist and the coach to have the type of information that a power meter provides. In fact, books such as *The Lance Armstrong Performance Program* (2), which was written by Lance Armstrong in conjunction with his long time coach Chris Carmichael, outline training with a power meter and the great benefits that come along with it. A similar and more in depth book on training was written by Joel Friel and is titled, *The Cyclist's Training Bible 3rd Ed.* (7). This book explains the numerous benefits that can be obtained from training with a power meter, along with ways in which one can go about implementing the use of one in their training regimen.

Publications such as these have brought techniques involved with training with a power meter to cyclists everywhere. Not only has this affected the way cyclists train, but also how power meters have been developed. With such a high demand on equipment that are accurate, lightweight, and easy to use, manufacturers have come up with newer and better ways of making power meters. Thus, bringing a tool that was once only used on stationary bicycles in laboratories, to the everyday cyclist who is looking to improve their performance on the bicycle.

Purpose of the Study

When a person starts to ride a bicycle uphill they begin to notice that with a lighter bicycle it seems much easier for them to ride. This perceived easier effort is correlated to a decrease in power output measured in watts. On the other hand, this same person will notice that when they are riding a heavier bicycle uphill the workload seems to be dramatically increased as well as the time it takes for them to reach the summit of the climb. This phenomenon is classified as the power-to-weight ratio and is a limiting factor in athletic performance.

Historically cyclists have always looked to have their bikes made out of the stiffest and lightest materials to improve their ability to ride uphill. This study was intended to quantify the benefits that the cyclists themselves obtained when riding a lighter bicycle uphill. To do this, measurements of each ride were taken in the form of watts produced. It was the purpose of this study to use multiple uphill time trials, one weighted and one not, to demonstrate the effect of added weight on power and time while cycling uphill.

CHAPTER II

METHODS

Subjects

Thirteen competitive bicycle racers were the subjects used for this research. Each of these subjects trained over 8 hours every week on their bicycles and had spent at least the previous 1.5 years training at very high intensities.

Apparatus

Each subject's bicycle had a Saris PowerTap SL 2.4 as a rear wheel hub to analyze the differences in both speed and power output between the two trials. The Saris computers that processed the information from the rear hub were programmed to obtain the subject's power (watts), torque (inch-pounds), speed (mph), and cadence (rpm) every second from the time the subjects started pedaling until they reached the summit of the climb.

Procedures

Prior to testing, the subjects signed informed consent and completed the Physical Activity Readiness Questionnaire (PAR-Q) developed by the Canadian Society for Exercise Physiology with support from Health Canada (3). Each subject had the testing procedures explained and their PAR-Q reviewed for any problems. Each subject's height and weight were also recorded for precise power analysis.

Once ready to ride, the subjects performed two hill climbs in a single exercise session up a 1.78 mile hill on which they have previously trained. During one climb 1.0

kg of sand was added to a water bottle on the bike frame to determine the difference in wattage per gram of weight added to the bike. The order in which the bikes were weighted was randomized to keep the riders from knowing if they had the bottle filled with 1.0 kg of sand or if they had the one that was empty. The subjects were allowed 30 minutes to recover following the first hill climb before starting the next one so that they could have at least a 2:1 ratio of recovery to workout time. During this time period the subjects were allowed to sit down, ride around, eat food, drink liquids, or go through whatever process they were used to for recovering from their initial effort. After the thirty minutes were up the subjects completed their second time trial.

The hill the subjects climbed for this experiment was 1.78 miles in length with an average gradient of 16.47% and a maximum gradient of 18%. The total elevation gain for the entirety of the climb was 545 feet.

Analysis

After the testing procedures were completed, each subject's data from their ride was downloaded onto a laptop computer to be calculated using the Saris Power Agent Software (See Figure 1). The Saris Power Agent Software displays, in graphical form, the measurements that the PowerTap takes each second during a ride. The graph then allows the viewer to analyze each and every part of a ride. It was graphical forms such as the one displayed below that were taken of each rider so that their power, speed, cadence, and time could all be calculated for each trial run. A large advantage of using the Saris PowerTap SL 2.4 was that the margin of error was less of a worry. This is because the

Saris PowerTap SL 2.4 has been determined to be statistically accurate to the +/- 1.5% level when taking power measurements (6).

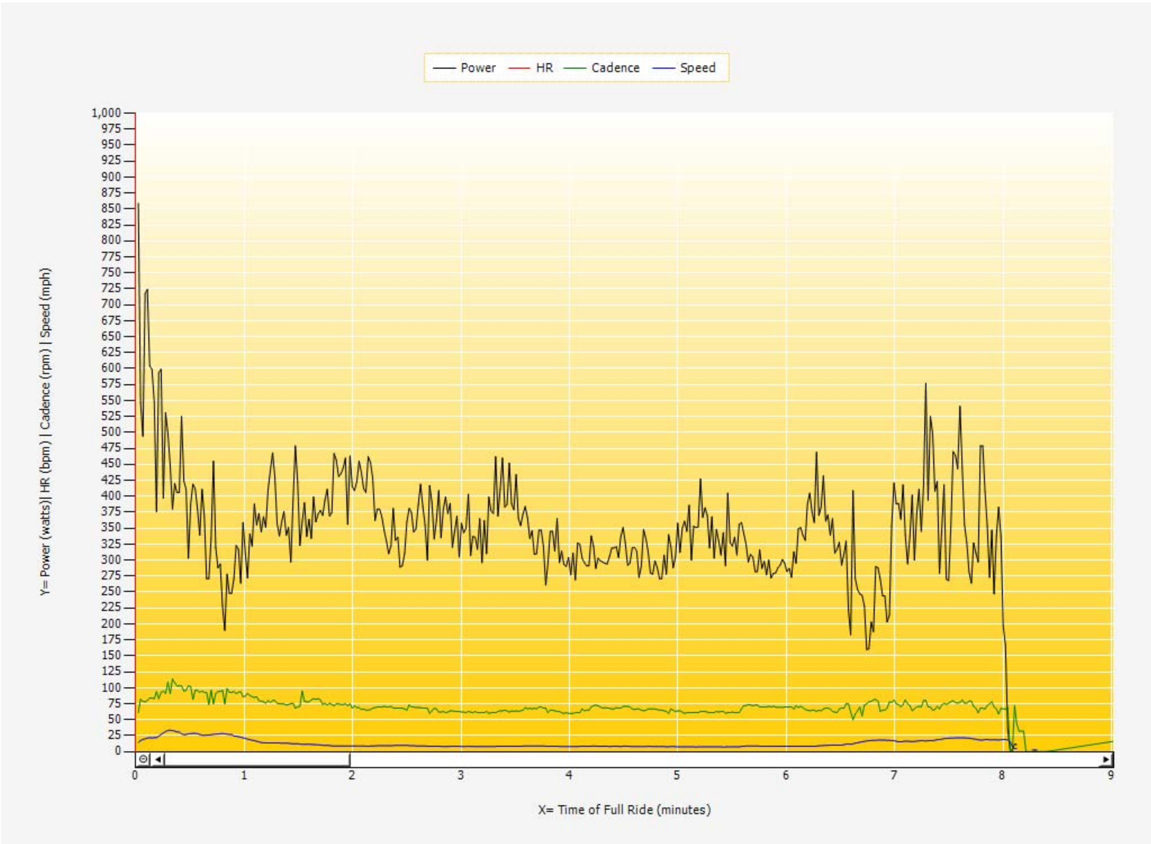

Figure 1 - Power Graph Developed By Power Agent Software

CHAPTER III

RESULTS

In this experiment thirteen avid cycling adults with an average age of 32 years old and a standard deviation of 12 years were tested. While all of the subjects used were avid cyclists, and many were also very accomplished racers (See Table 1). The average category of racer that was tested in this study was a 3, while a few subjects ranked as high as category 1 racers and raced for major domestic teams. Since all cycled on a regular basis, the average weight of the subjects was only 162 pounds with the standard deviation from that being just over 23 pounds.

Table 1. Demographic Data Of Test Subjects

Subjects' Demographic Data
Average Age: 32.69 $\pm$ 12.00
Average Weight: 162.31 $\pm$ 23.42
Average Racing Category: 3.54 $\pm$ 1.52

The maximum wattage output that was recorded with 1.0 kg weight added to the bicycle increased drastically. This was consistent among all of the test subjects except two, with an average increase of 53.77 watts being produced. The standard deviation from this mean was only 38 watts, which is a pretty small amount considering the large amount of maximal wattage the subjects produced during their rides.

Another factor that was consistent among all of the subjects, except one, was an increase in the amount of time it took them to reach the summit of the climb with the 1.0 kg weight added to their bicycle. The average amount of time that was added onto their climb with the weight was an extra 21 seconds.

When the subjects had the 1.0 kg weight added to their bicycles for the climb, a decrease in average power output was measured. Five subjects showed a significant decrease in their average power output on their weighted test; one subject's power output remained the same for the two runs, while the remaining seven subjects showed an increase in their wattage with the extra weight. The average difference in power output for the entire group of test subjects with the 1.0 kg weight added to their bicycle during the hill climb was -3.46 watts, with the standard deviation from that mean being 2.45 watts.

Table 2. Mean Differences With Added Weight

Mean Differences With Added Weight		
Maximum (watt)	**Mean (watt)**	**Time (sec)**
53.77± 38.02	- 3.46± 2.45	- 21± 14.85

Table 3. Subject Results - Standard And Modified Bicycle Weight

Subject	Racing Cat.	Max Watt	Avg. Watt	Time	Max Watt	Avg. Watt	Time
#	(1-5 Scale)	No Weight	No Weight	No Weight	(+ 1 kg)	(+ 1 kg)	(+ 1 kg)
1	4	622	300	11:27	624	288	11:35
2	1	485	321	8:32	493	314	9:39
3	1	668	322	9:06	702	334	8:16
4	5	393	209	11:55	400	221	12:25
5	2	975	324	8:49	1077	329	9:00
6	4	490	318	9:30	487	261	10:29
7	4	370	204	11:19	639	211	11:30
8	4	1106	311	10:08	1011	300	10:57
9	4	625	233	12:45	628	221	13:32
10	4	732	309	10:40	1046	321	10:45
11	1	859	345	8:03	956	350	8:08
12	2	956	358	8:13	1050	358	8:25
13	5	553	233	11:59	420	234	12:10
Average	3.154	679.538	291.308	10:11	733.308	287.846	10:32

When examining the graphs produced by the Power Agent Software on the various subjects, there are many similarities present throughout the duration of their rides. The most notable of these similarities is in the peaks and valleys present in their power measurements at similar points in time. The peaks were prevalent at points in the hill where there was a very slight incline in the road, while the valleys were prevalent at points in which the hill kicked up to its steepest gradient, and finally, the power levels remained more constant when the gradient on the hill remained constant for an extended period of time. The majority of the subjects also seemed to have an increase in their power output on the very last section of the climb as they sprinted through the finishing line.

CHAPTER IV

DISCUSSION

The results of this experiment showed exactly what was expected to be seen as far as maximum wattage and total time were concerned. The unexpected result, however, was the overall decrease in average wattage when the subjects rode uphill with added weight on their bicycles. While this did not occur in every subject, the overall average of all of the subjects was enough to show a -3.462 watt power output for the all of the subjects as a whole, while carrying the extra weight.

One possible reason for this was due to the extreme gradient at which the subjects were tested during their uphill time trials. The majority of the previous tests done on power output and uphill time trials were done on longer climbs (usually close to 5 miles) with much easier gradients (usually 4-6%). Since the subjects in this study were required to climb up a much more extreme gradient (16-18%), it is reasonable to consider the possibility that they were not able to completely recover from one effort to another within a 30 minute time span. Not being fully recovered could drastically change the results from one ride to another on a hill with a length and gradient of the magnitude used in this test.

The biggest possible source of error from the data would come from this lone factor. During testing it was assumed that the results gained from these subjects could be applied to almost any other avid cyclist. In many instances this would be the case, but with a rider of higher abilities the time for recovery needed would most likely be less, thus resulting in less of a decrease in average wattage, if any at all. To be completely sure that this is the case, however, a much larger group of subjects would be required, ranging from active enthusiasts to highly trained professionals. It would also be beneficial to test the subjects on multiple hills of multiple lengths and gradients, while also considering having a full day’s rest in between each subject’s tests.

The results of this experiment are significant within the context of exercise because they apply to any increased amount of weight that a cyclist has to deal with while riding uphill. The results show us that when weight is added onto a cyclist or their bicycle, the effort (power measured in watts) required to maintain the same speed they are able to travel with a lighter bicycle was significantly increased. Anyone hoping to improve the speed and efficiency with which they are able to cycle uphill should understand all of this information thoroughly and that is why this experiment was conducted.

The data obtained can be broken down to see how each gram of added weight affected the outcome of subject group’s rides. The data might not seem significant at first sight, but when you consider the fact that a rider can save thousands of grams by switching from one bicycle frame material to another, the numbers begin to add up quickly. It’s numbers like these that can play a huge role in the outcome of a race involving any significant gains in elevation.

Practical Applications

The purpose of this experiment was to have numerous cycling enthusiasts perform a maximal exercise test on a challenging hill to determine how added bicycle weight effects power output and time. It is important to understand the ways in which an increase in weight affects these factors because it directly impacts how light a rider would want their bicycle and/or their own body to be when training for a specific event.

As far as professional cyclists are concerned, major tour races such as the Tour de France, Giro de Italia, or Vuelta a Espana, require racers to spend multiple days of racing in the mountainous regions of the respective countries. It is considered to be nearly impossible for a rider to win any of the three Grand Tours if they are not competitive when racing in the mountains. The results obtained in this experiment clearly showed the benefits obtained from using a lighter bicycle when riding uphill. From the data acquired, it may be assumed that the longer the hill is the more extreme the differences will be between a heavier and a lighter bicycle. Further experimentation with a larger population of subjects and multiple hills is recommended for confirmation. A wider range of subjects and hills would help to prove or disprove this experiment's overall validity and that of the results that were obtained.

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