

A Novel Gear-shifting Strategy Used on Smart Bicycles

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Abstract. During cycling, riders can move shift-levers to obtain different gear-ratio or cadence in order to satisfy different external environments and cardiovascular requirements such as high power, low pedaling force, low muscle stress, and etc. Prior researches of human cycling focus on satisfying the specific one or two requirements to determine the optimal cadences. But most inexperienced riders cannot judge the moment to shift gears to obtain the optimal cadence. Such actions will injure rider's body, and riders cannot make use of the derailleur system in the correct way. This study used fuzzy control theory to integrate all requirements in cycling and developed the strategy about the correct up-shifting or down-shifting moment depending on all cardiovascular requirements and external physical environments. Finally, this study proposed a more complete strategy to certify rider's health.

Keywords: cardiovascular requirements, gear-shifting strategy, bicycle.

1. Introduction

In recent years, multi-speed bicycle has become the market stream. A multi-speed bicycle is composed of lots of components, including frame tubes, brakes, derailleur systems and transmission parts. A complete derailleur system consists of five components: chainwheel and freewheel, front and rear derailleurs, shift levers, cables and a chain. The chainwheel and freewheel include several sprockets, each having different numbers of teeth. There are two shift levers connected to the front and rear derailleurs through cables. Cyclists move the two shift levers to drive derailleurs guiding the chain to engage larger sprockets, or guiding the chain to drop to smaller sprockets. It can get different gear-ratios for cyclist.

When riding a bicycle, the cyclist makes significant use of both the strength in legs and the cardiovascular system. Change gear-ratios can make riders feel more comfortable. Cyclists can choose a low gear-ratio to pedal at high cadence and low torque, or choose a high gear-ratio to pedal at low cadence and high torque. It has many factors to decide which gear-ratio to be selected. The optimal gear-ratio can get the optimal cadence. Cyclists will feel comfortable if they pedal at their optimal cadence. When external physical environment changes, cyclists can change the gear-ratio to get their optimal cadences. It is important to decide what the optimal cadence is, and how to choose an optimal cadence when external physical environment changes. There are lots of factors which influence how to choose the optimal cadence. For example, muscle stress, joint moment, human power, torque, and etc. In the past, many researches focused on one or two factors to determine the optimal cadence. From these researches, riders can get some rules to help them riding bicycle at the optimal cadence. But riders still feel uncomfortable because there are some factors neglected. For example, riders can choose the optimal cadence between 50 and 60 rpm from the ergonomic point of view, but such cadence may make knees easy to get injury in biomechanics.

There are such researches about the time to change gear-ratio to get the optimal cadence when the external physical environment has been changed. Also, an inexperienced rider cannot judge the moment to use the shift-levels to get the optimal cadence. So they cannot make use of the derailleur system in a correct way. However, there are no researches about choosing the optimal cadence by considering all factors mentioned above. But on the market, there are some products which can change gears automatically such as

Browning SmartShift and Shimano AutoD. But the gear changing criteria of these products only depends on the bicycle velocity. In fact, it is not enough for humans. According to the above statements, the purpose of this research is to develop a model considering all factors affecting the human optimal cadence. In addition, this study also provides rules about how to choose a correct gear-ratio as the external physical environment changes.

2. Preliminary Details

In order to ride at the optimal cadence, there are lots of researches defining optimal cadence from different standpoints. In 1986, Rob Redfield and M. L. Hull developed a biomechanical model to compute stress and moment when riding bicycles. They found the relation between joint moments and pedalling rates with experiments. They tried to minimize the sum of the average absolute joint moments during constant power riding. They found the optimal cadence was about 95 to 105 rpm [1], and experimented for lowering muscle stress or joint moment. From the experiment, they got the high connection between muscle stress and other factors (such as pedal force, and ankle moment) [2]. In 1988, M. L. Hull and his co-workers chose to lower muscle stress. And they developed a more sophisticated model to assess the influence of cadence on the muscle stress. They minimized the muscle stress and got the optimal cadence about 95 to 100 rpm [3].

In 2000, Anthony P. Marsh [4] and his co-workers made an experiment. They divided three groups of cyclists: trained cyclists, runners and less-trained cyclists. These cyclists experimented at optimum cadence and optimum output powers. The trained cyclists and runners rode at 100 W, 150 W, 200 W, and 250 W; the less-trained cyclists rode at 100 W and 150 W. A simulation and analysis about the specific neuromuscular activation, force, stress and endurance based on a dynamic model carried out at different rates of 75, 90 and 105 rpm at a fixed power output of 265 W [5]. Wilson [6] indicated that everyone should be able to work easily at one-third of maximal oxygen uptake, but exceeding two-thirds of maximal oxygen uptake for a long duration may require considerable training. For a non-trained person, the maximum oxygen-absorption rate (VO₂ max) is assumed to be about 50 ml/s. When a rider is using about a third of his maximum oxygen-absorption rate, the power output is about 0.1 hp (75W). He thought that common people can work under these conditions for several hours without suffering fatigue.

One experiment measured the preferred cadence and the lowest oxygen consumption cadence. Eight cyclists and eight non-cyclists pedalled at 200 W. The preferred cadence for cyclists is 75 to 95 rpm. But the lowest oxygen consumption cadence for cyclists is 50 to 60 rpm [7]. From these researches, it is important to consider all factors influencing the optimal cadence. Because it has an obvious difference from different points of view.

The results here can be concluded as:

1. Riding bicycles emphasize the strength in legs more than the cardiovascular system.
2. Higher cadences make rider comfortable and can ride for a long time, but it costs more oxygen consumption.
3. Cyclists have a stronger cardiovascular system than non-cyclists, so they can use less oxygen consumption at the same cadence.
4. High pedalling cadence is not totally good for human power.
5. The relationship between human power and torque conforms to the theory.

There is a lot of optimal pedalling cadence based on different viewpoints. From above literatures, this study takes the optimal pedalling cadence range is between 60 to 90 rpm. The range will be the criterion of the new gear-shifting strategy.

3. Fuzzy Logic Controller

From the conclusions of previous chapters, it is obvious that many factors affect human cycling and it is difficult to obtain a unique criteria for the optimum cadence. Therefore, this study then uses the fuzzy logic controller to simulate human reasoning during cycling. Fuzzy logic first was introduced by Professor Lotfi Zadeh in 1965 [8]. It can be extremely useful not only in engineering and technological sciences, but also in

social sciences, eliminating the difference in the approaches between natural and social sciences. The fuzzy logic controller is a tool for processing a fuzzy form of information in a non-fuzzy or fuzzy scheme of reasoning. As shown in Fig. 1, a simple fuzzy logic controller contains a fuzzification interface, a fuzzy knowledge base, an inference engine, and a defuzzification interface.

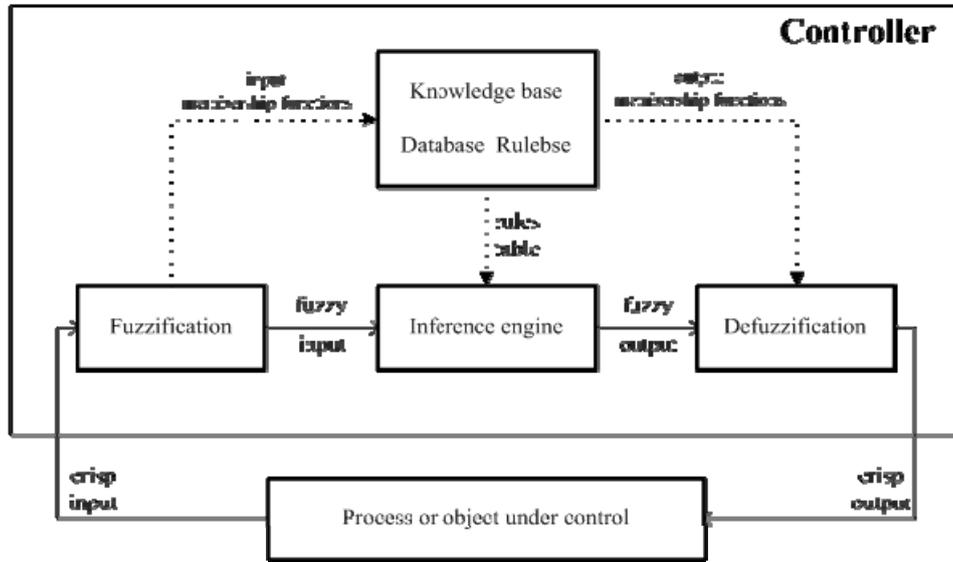


Fig. 1: The fuzzy logic controller (a basic structure)

According to literature reviews, this study chooses the pedal cadence range to construct the fuzzy set. Riders can feel comfortable riding in this range because it costs small loading of forces, muscle stress, joint moment, neuromuscular, and VO₂. This study uses two input variables, velocity (v) and pedal cadence (u), and one output variable, gear-ratio (g). The membership functions are shown in Fig. 2.

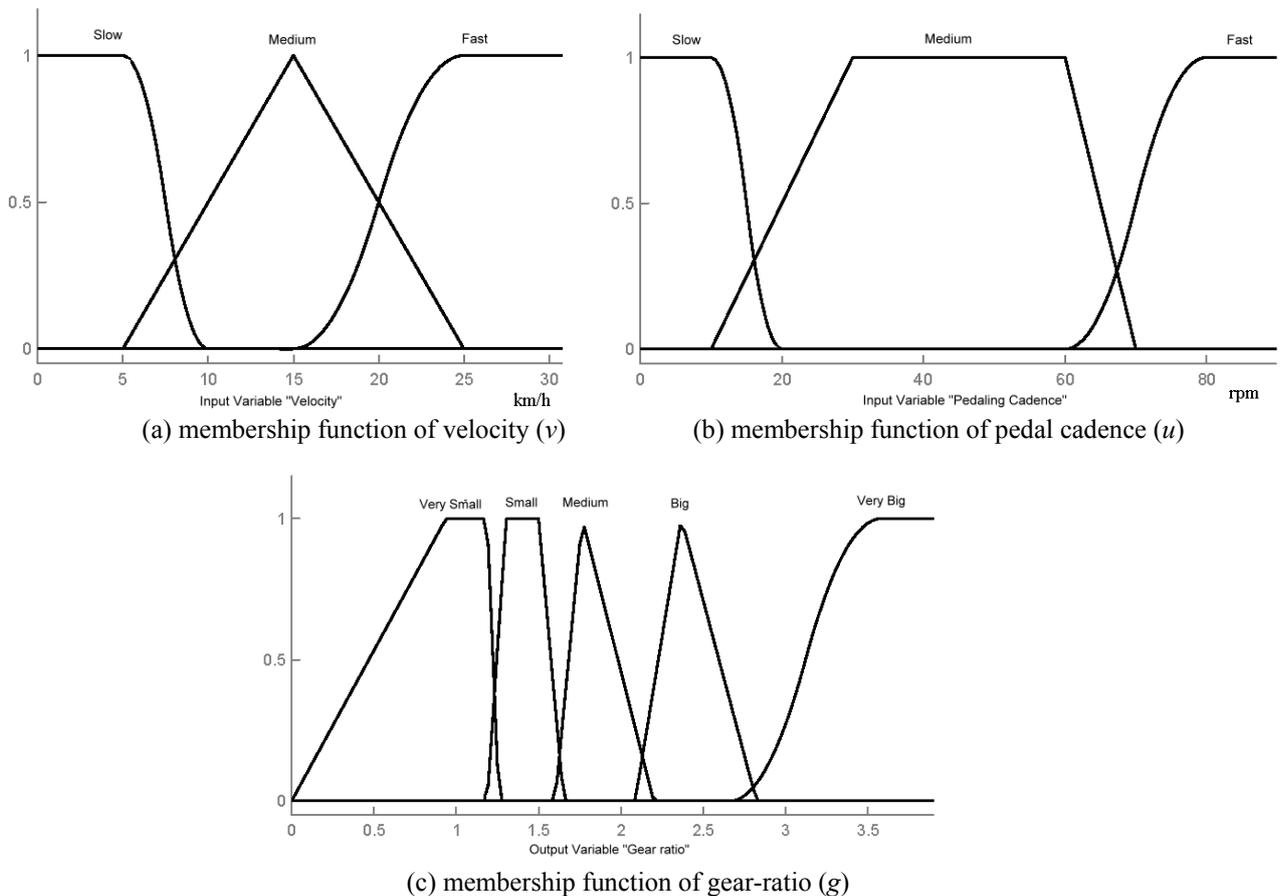


Fig. 2: membership functions of input and output variables

There are two inputs and one output variables, nine fuzzy rules can be constructed as shown in Table 1. The general form of the rules in this case of two-input-single-output system is:

Ruleⁱ: IF (*v* is *V_i*) AND (*u* is *U_i*), THEN (*g* is *G_i*), *i*=1 to 9.

where *v*, *u* and *g* are linguistic variables representing the velocity, pedal cadence and gear ratio, respectively. *V_i*, *U_i* and *G_i* are the linguistic values of the variables *v*, *u* and *g*. Take the rule 3 in Table 1 for an example, if the input velocity is slow and pedal cadence is fast, it means that the gear ratio is small at the moment, and the pedal cadence is too fast. Therefore, the output gear ratio should be change to a medium one in order to lower the pedal cadence and increase the velocity.

Table 4.1 Fuzzy rule base

| Rule # | IF | | THEN |
|--------|-----------------------|----------------------------|-------------------------|
| | Velocity (<i>v</i>) | Pedal cadence (<i>u</i>) | Gear-ratio (<i>g</i>) |
| 1 | Slow | Slow | Very Small |
| 2 | Slow | Medium | Small |
| 3 | Slow | Fast | Medium |
| 4 | Medium | Slow | Small |
| 5 | Medium | Medium | Medium |
| 6 | Medium | Fast | Big |
| 7 | Fast | Slow | Medium |
| 8 | Fast | Medium | Big |
| 9 | Fast | Fast | Very Big |

This study used the max-min composition as the inference method. It is the most famous one and suitable for all situations. Since the fuzzy rule base consists of compositional relations of inference: $R=(V \cap P) \rightarrow G$, the max-min composition is used as the fuzzy implication. Take the nine rules in Table 1 for example, the “IF” side is taken the “AND (MIN)” operation as shown in the following equations:

$$\mu_{G_i}(g) = \mu_{V_i}(v) \cap \mu_{U_i}(u), \quad i=1 \text{ to } 9 \quad (1)$$

And the final inferred consequent *G* according to the “OR (MAX)” operation is shown in the following equations:

$$\mu_G(g) = \mu_{G_1}(g) \cup \mu_{G_2}(g) \cup \mu_{G_3}(g) \cup \dots \cup \mu_{G_9}(g) \quad (2)$$

Finally, the center of area (COA) method is selected as the defuzzification strategy. The operation is shown in the following equation:

$$g^* = \frac{\int_g \mu_G(g) g dg}{\int_g \mu_G(g) dg} \quad (3)$$

This method determines the center of area (g^*) below the combined membership function. The center of area means the desired gear ratio. It can be compared to the current one. If the desired gear-ratio is larger, it means the fuzzy logic controller suggests a larger gear-ratio than the current one. Therefore, a up-shifting command must act on the derailleur system to obtain a larger gear-ratio.

4. Experimental Results

In order to implement the proposed fuzzy logic controller, a Browning 12-speed SmartShift bicycle (Fig.3) with an 8051 based control architecture is used for the hardware. The fuzzy logic controller is implemented in the ECU (Electrical Control Unit) box.



Fig. 3: Browning SmartShift System

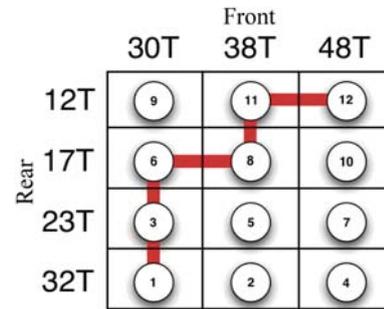


Fig. 4: Gear-shifting sequence

After completing the fuzzy logic controller, it needs to choose the gear-shifting sequence. In 2007, Lin et al [20] developed a gear-shifting sequence to produce the minimum power change during gear-shifting. Taking it on the Browning SmartShift system can get the optimum gear-shifting as shown in Fig 4. Taking this result as the gear-shifting sequence will make the shifting strategy more comprehensive.

After setting up the software and hardware, road tests can be performed to test the system. In order not to shift gears so frequently, the system gets the velocity, pedaling cadence and output a gear-ratio every 3 seconds. As shown in Fig. 5, between points 5 and 23, the velocity increases. It means that the rider is on a downgrade, so the gear-ratio is changed to a bigger one. On the other hand, the velocity and the pedaling cadence decrease between the points 23 and 27, it means that the rider is on an upgrade. Therefore, the gear-ratio is changed to a smaller one in order to make the rider feel more comfortable. Between points 1 and 5, the bicycle starts from the rest, so the gear-ratio is selected to a medium one in order to prevent the pedaling cadence excessively fast.

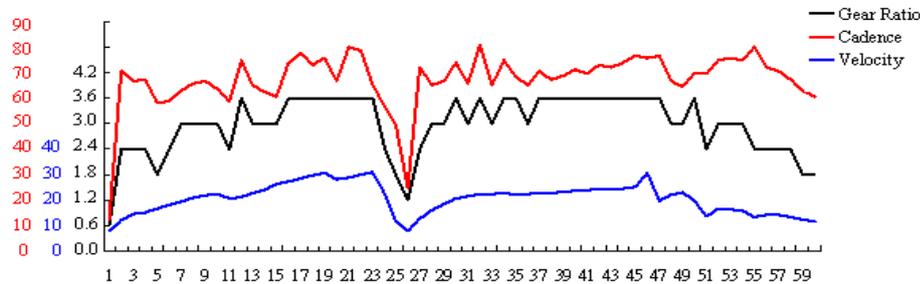


Fig. 5: Road test results (I)

There is another rider's test on the same route as shown in Fig 6. Between points 13 and 17, the velocity and the pedaling cadence increase. It means that the rider is on a downgrade; therefore the gear-ratio is selected to a big one. On the other hand, between the points 23 to 25, the velocity and the pedaling cadence decrease suddenly, it means that the rider is on an upgrade. For this reason, the gear-ratio is changed to a small one. And there is a similar appearance between the points 35 to 37.

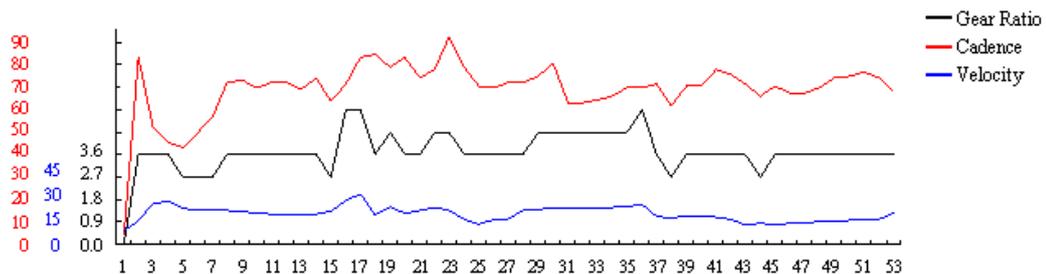


Fig. 6: Road test results (II)

5. Discussions and Conclusions

Based on the experimental results, it is obvious that the fuzzy logic controller works well to improve the gear-shifting performance during riding bicycles. The controller changes gears depending on the velocity and the pedaling cadence. The results show that it can change gears not only matching the physical environments but also taking care of the riders. Therefore, it changes gears more stable and correct. And it changes not so frequently that can make riders easy to operate the bicycle and feel more comfortable. The pedaling cadence range of the different riders is from 60 to 85 rpm.

There are many factors influencing the riders' performances. But the point is that if the riders know how to choose the gear-ratio and ride at the optimal cadence, then he or she can get the best performances or most comfortable feelings. In this study, the new shifting strategy is completed by fuzzy logic control theory. And it was implementing using the Browning SmartShift system. It can test and get experiment data after combining the software and hardware. Integrating the fuzzy logic controller with the optimal gear-shifting sequence make the strategy more complete. The optimal gear-shifting sequence can decrease power lose during gear-shifting

6. References

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