

New index for evaluating pedaling techniques using the pedaling efficiency index with gradually increasing load

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2 **Abstract.** Purpose: Measuring the pedal force vector during bicycle pedaling has recently become easy,
3 and studies have been conducted using mechanical efficiency (the ratio of an effective driving force to
4 total pedaling force); however, the relationships between these forces were not considered. This study
5 aimed to show that the relationship between these forces can be linearly regressed under gradually
6 increasing load conditions and propose that the slope parameter can serve as a new index for evaluating
7 pedaling skills. Methods: Twenty-eight participants performed the experiment in which the load was
8 increased every minute until the maximum load was exerted. Using sensors installed on both bicycle
9 cranks, the pedaling force vector was divided into tangential and radial components to determine the
10 total pedaling and effective driving forces per minute. The maximum load force and efficiency index
11 were calculated. Results: Our results showed a strong linear relationship (coefficient of determination:
12 0.982, 95 % CI 0.909–0.996) between the total pedaling and effective driving force. The slope
13 parameters from this regression exhibited significant correlations (-0.560 and -0.674) with the
14 maximum load force and efficiency index during maximum exertion, respectively. These correlations
15 highlight the slope parameter potential for capturing pedaling characteristics. Conclusions: The slope
16 parameter derived from the linear regression between the total pedaling force and effective driving
17 force reflects individual pedaling characteristics. This parameter stands out as a promising new index
18 for evaluating pedaling motion, offering insights into participant-specific pedaling behaviors.
19 Consequently, this novel index could be instrumental in assessing and analyzing pedaling skills.

20
21 **Keywords:** bicycle pedaling, pedaling force vector, force efficiency, linear regression, efficiency index

22 23 24 1. Introduction

25
26 When studying bicycle-pedaling motion, examining how the participant moves, the force
27 applied to the pedals, and the crank rotation is important. Therefore, previous studies on pedaling
28 measured body movements using motion capture devices [7] [20] or the force applied to the pedals
29 [14] [19] and crank rotation [1] [5] [6]. Generally, power is used as the load when pedaling, and to
30 output that power value, the cyclist selects what muscle activation pattern, or pedaling movement,
31 to perform.

32 When considering this bicycle pedaling movement, the efficiency of how much energy the
33 body needs to output a certain propulsive force (power value) is important. Similarly, if the
34 participant can pedal more efficiently to achieve a specific power output, it can be considered that
35 they have developed effective pedaling skill. There are two types of efficiency: kinematic
36 efficiency (gross efficiency), calculated from the ratio of the total energy exerted by the body—
37 measured from exhaled breath like Vo₂max — to the propulsive force of the bicycle [4] [10] [12]
38 [13] [16]; and mechanical efficiency index (FE), calculated from the ratio of the effective driving
39 force to the total pedaling force [3] [6] [10] [11] [15] [21]. To measure this pedaling FE, measuring
40 both the tangential and normal forces applied to the pedal is essential. Previously, the force vector
41 acting on the pedal was measured in a laboratory. However, the force vector acting on the pedal
42 can now be easily measured using commercially available equipment [2] [17] [18], and even
43 ordinary cyclists can now measure the pedaling vectors and efficiency index. Thus, even when the
44 same output load (power value) is being produced, efficiency changes depending on the pedaling
45 motion. Therefore, the FE has been studied in relation to the muscular strength exerted [6] [21]
46 and pedaling skill [10] [11] [15]. Because the FE is easy to measure, an objective index of the
47 participant's pedaling motion is now routinely used. However, the FE of pedaling does not

1 necessarily correspond to fluctuations in kinematic efficiency [10], and changes depending on the
2 load power, cadence (number of revolutions of the crank), and body weight [3] [8]. Therefore,
3 understanding a participant's actual pedaling characteristics and skills using the FE alone is
4 challenging.

5 Our preliminary study [9] showed certain characteristics in the change in pedaling force when
6 the pedaling load is gradually increased and that these characteristics are related to the maximum
7 pedaling force. This suggested the possibility of obtaining an index other than the FE. Therefore,
8 this study aimed to propose a new index that can evaluate the characteristics of pedaling motion,
9 different from the FE that has been used.

12 2. Methods

14 2.1 Participants

15 Twenty-eight healthy adult male amateur cyclists participated in the experiment. Participants
16 included some competitive and recreational cyclists, with a mean age of 39.4 ± 9.4 years.
17 Participants provided comprehensive written consent before the experiment and authorized the use
18 of their experimental data for research. This study is a non-interventional observational study
19 using existing information obtained from the research participants and was conducted following
20 the Ethical Guidelines for Medical and Health Research involving Human Subjects.

22 2.2 Experimental design

23 A schematic of the experimental setup is shown in Figure. 1. The experiment was conducted
24 using a bicycle equipped with a pedaling monitor sensor (SGY-PM900H90, manufactured by
25 Pioneer) installed on a load device (Powerbeam Pro, manufactured by CycleOps). Before
26 conducting the experiments on each participant, the pedals were changed to match the participant's
27 shoes, and the saddle position was adjusted to match the participant's physique.

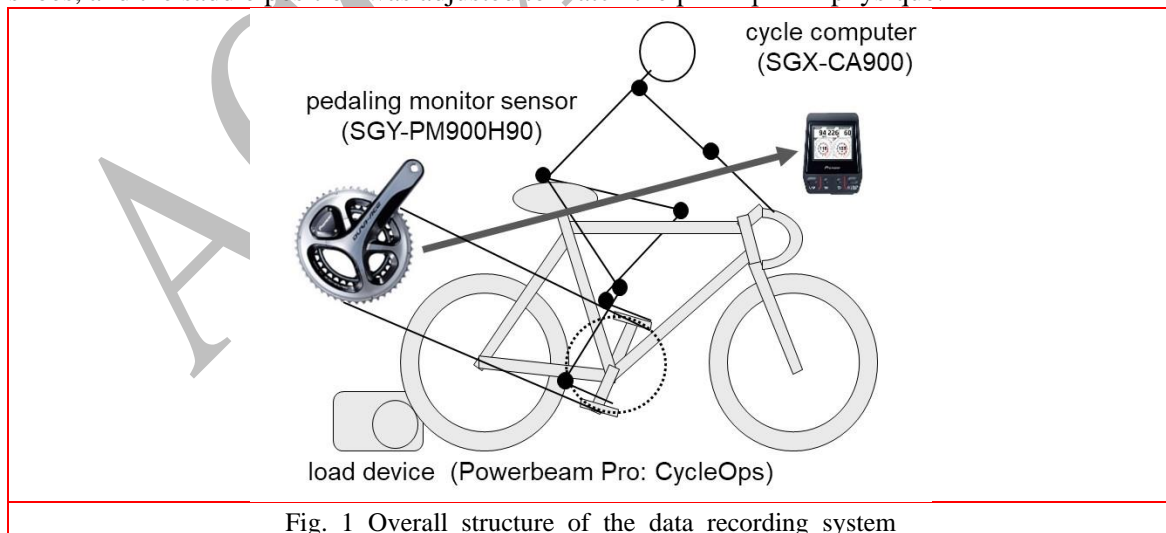


Fig. 1 Overall structure of the data recording system

28 Figure 2 shows an example of the experimental protocol and measurement results. First, the
29 participant started pedaling with a low load intensity of approximately 150 W (equivalent to 75 W

1 with one leg) and performed a 1 min preparatory movement to stabilize the pedaling motion.
 2 Measurements were started after 1 min had elapsed, and the load was increased by 50 W
 3 (equivalent to 25 W for one leg) every minute. After applying a sufficiently high-intensity load
 4 through a gradual increase, the measurement was terminated at the participant's discretion when
 5 the load could no longer be maintained by pedaling while sitting. The load device used in the
 6 experiment **could** maintain a preset constant intensity even if the cadence changed; therefore, the
 7 cadence during the experiment was set at **the participant's direction**.

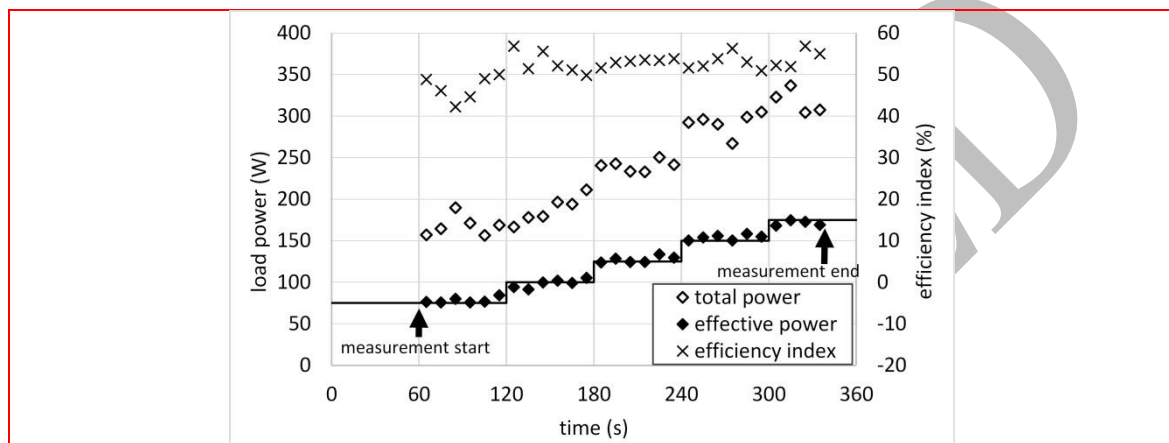


Fig. 2 Experimental protocol and example of measurement

9
 10 The pedaling monitor sensor has a built-in sensor that can measure the **tangential and radial**
 11 **pedaling force on each (left and right) bicycle crank and the pedaling force vector**. **This pedaling**
 12 **force vector is measured** every 30° of crank rotation **using the built-in crank rotation sensor**. **The**
 13 **measured pedal force vector and cadence calculated from the rotation sensor** were sent to a cycle
 14 computer (SGX-CA-900, Pioneer) every second and recorded. Inside the cycle computer, the load
 15 power value and efficiency index were calculated from the pedal force vectors and cadence. **The**
 16 **efficiency index is calculated using only the pedaling force vector; hence, cadence does not affect**
 17 **it**. Figure 2 shows the load power and efficiency index recorded every second and the power value
 18 of the total pedaling force calculated from these values as an average every 10 s to make it easier
 19 to observe the fluctuations.

20 Table 1 presents the characteristics of the participants and their workloads. The load on the
 21 participants started at approximately 172 W on average and increased to approximately 329 W
 22 (more than five times the body weight) by the end of the experiment.

Table 1 Participant condition and experimental conditions

		average ± SD
age		39.4 ± 9.4
body weight (kg)		63.3 ± 7.6
height (cm)		170.4 ± 5.5
cadence (rpm)		101.6 ± 7.5
load power (W)	from	171.8 ± 15.4

	to	328.6 ± 39.5
power-weight ratio (W/kg)	from	2.75 ± 0.40
	to	5.26 ± 0.85

2.3 Data treatment

The data analysis method is described as follows. The cycle computer recorded the pedal force vectors (tangential and normal torque values for every 30° of crank angle), cadence, efficiency index, and load power values every second. The recorded data file was sent from the cycle computer to a personal computer, and data processing was performed. From the measured data, the force efficiency index was calculated using Eq. (1), where θ represents the crank angle.

$$\text{force efficiency index} = \frac{\int_0^{360} F_E(\theta)}{\int_0^{360} F_{total}(\theta)} \quad (1)$$

The numerator of this equation is the effective driving force, and the denominator is the total pedaling force; hence, the total pedaling force can be calculated using the following Eq. (2).

$$\text{total pedaling force} = \frac{\text{effective driving force}}{\text{force efficiency index}} \quad (2)$$

Generally, when studying bicycle pedaling, power is often used to quantify the load. However, as mentioned above, previous studies have shown that efficiency indexes vary depending on the power, cadence, and body weight. In this study, power was calculated as the product of the force applied to the pedals and the cadence, which is not a good method for evaluating the force exerted by the muscles. Therefore, in our study, the load power was not used; however, to remove the variable factor, it was converted to force per body weight as follows: First, the load power value was converted to torque divided by the cadence, and then the torque value was divided by the rotation radius (0.17 m) of the pedal axis to convert it to the force applied to the pedal (kgf). Next, when sitting, the weight of the legs was used to push the pedals downward; therefore, the force applied to the pedal was divided by the body weight to calculate the force per body weight (%).

The total pedaling force, effective driving force, and efficiency index were averaged every minute from the beginning of the experiment. The participants increased the load every minute, and the measurement was stopped when they could no longer withstand it. Therefore, at the end of the measurement, the amount of data was < 1 min. However, this last value was the maximum exertion force for each participant and was calculated as the maximum exertion force per body weight (%) using the same calculation as above. The FE (%) at the time of maximum force exertion was calculated and used for subsequent analysis.

Regarding the force vectors in the tangential and normal directions, to observe the pedaling behavior of each participant, the average torque value was calculated for 1 min for a typical example and converted into force per body weight (%) using the method described above.

2.4 Data analysis

For each experiment involving 28 participants, the Pearson's correlation coefficient and the coefficient of determination between the total pedaling force and the effective driving force were calculated for each of the 56 left and right leg data, and the linear relationship was evaluated.

1 **Notably**, the load in this calculation was not the total force but the force applied to each crank.
 2 Regarding the correlation coefficient and the coefficient of determination, because the Fisher-
 3 transformed correlation coefficient follows a normal distribution, each calculated correlation
 4 coefficient was Fisher-transformed to obtain the average value and standard deviation, and then
 5 Fisher-inverse was transformed to obtain a 95 % confidence interval (CI).

6 For the data (N = 56), a linear regression analysis was performed using the least-squares
 7 method, with the effective driving force as the explanatory variable and the total pedaling force as
 8 the objective variable, and the slope and intercept parameters were calculated. Using this slope
 9 parameter as a reference, the correlation coefficients with other measured values and their 95 %
 10 CIs were calculated, and a test for non-correlation was performed. A $p < 0.05$ was considered
 11 statistically significant. We used JMP (Version. 17) for the statistical calculations.

14 3. Results

16 3.1 Regression data

17 Figure 3(a) shows the relationship between the effective driving force normalized by body
 18 weight and the efficiency index for three representative participants (A, B, and C). The horizontal
 19 axis shows the force per body weight rather than the load (power) during pedaling; however, the
 20 relationship with the efficiency index differs for each participant, and the relationship is not linear.

21 In contrast, the relationship between the effective driving force and the total pedaling force nor-
 22 malized by body weight (Figure 3 b) shows a linear relationship for each participant.

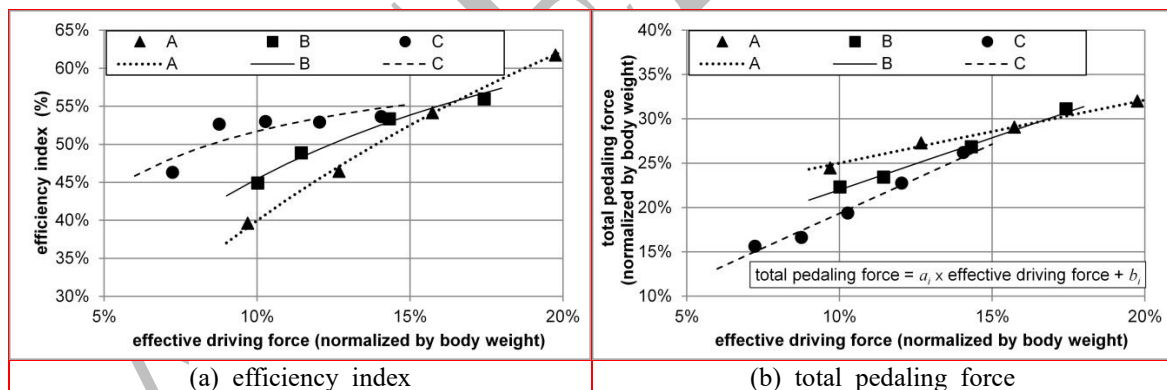


Fig. 3 Relationship between effective driving force normalized by body weight and (a) efficiency index or (b) total pedaling force for three representative participants (A, B, and C)

24 3.2 Regression parameter

25 To evaluate the linear regression of the effective driving force and total pedaling force for each
 26 participant, Table 2(a) presents the average values and 95 % CI of the correlation coefficient and
 27 coefficient of determination calculated from the 56 data points. The average values and 95 % CI of
 28 the slope parameter (a_i) and intercept parameter (b_i) of the linear regression are presented in Table
 29 2(a). Table 2(b) presents the calculated average values and 95 % CIs for the total pedaling force,
 30 effective driving force, and efficiency index at the maximum exertion force.
 31
 32

Table 2 Calculated values for evaluation of linear relationships
 (a) Correlation coefficient, coefficient of determination, and regression parameters

	average	95 % CI
r	0.991	0.953–0.998
r^2	0.982	0.909–0.996
slope parameter a_i	1.38	0.68–2.08
intercept parameter b_i	8.6%	-0.1–17.3

(b) Measured value under maximum exertion force condition

	average	95 % CI
total pedaling force	28.4 %	20.4–36.4
effective pedaling force	14.5 %	9.2–19.8
efficiency index	51.4 %	35.4–67.5

The value obtained from the linear regression results based on the data for each left and right pedal for all participants and the relationship between the slope parameter and the following four values were investigated: (a) the intercept parameter of the linear regression, (b) efficiency index (%) at the maximum exertion force, (c) effective driving force at maximum exertion (%), and (d) total pedaling force at maximum exertion (%). These relationships are illustrated in Figure 4, showing data from three participants, A, B, and C, as representative examples.

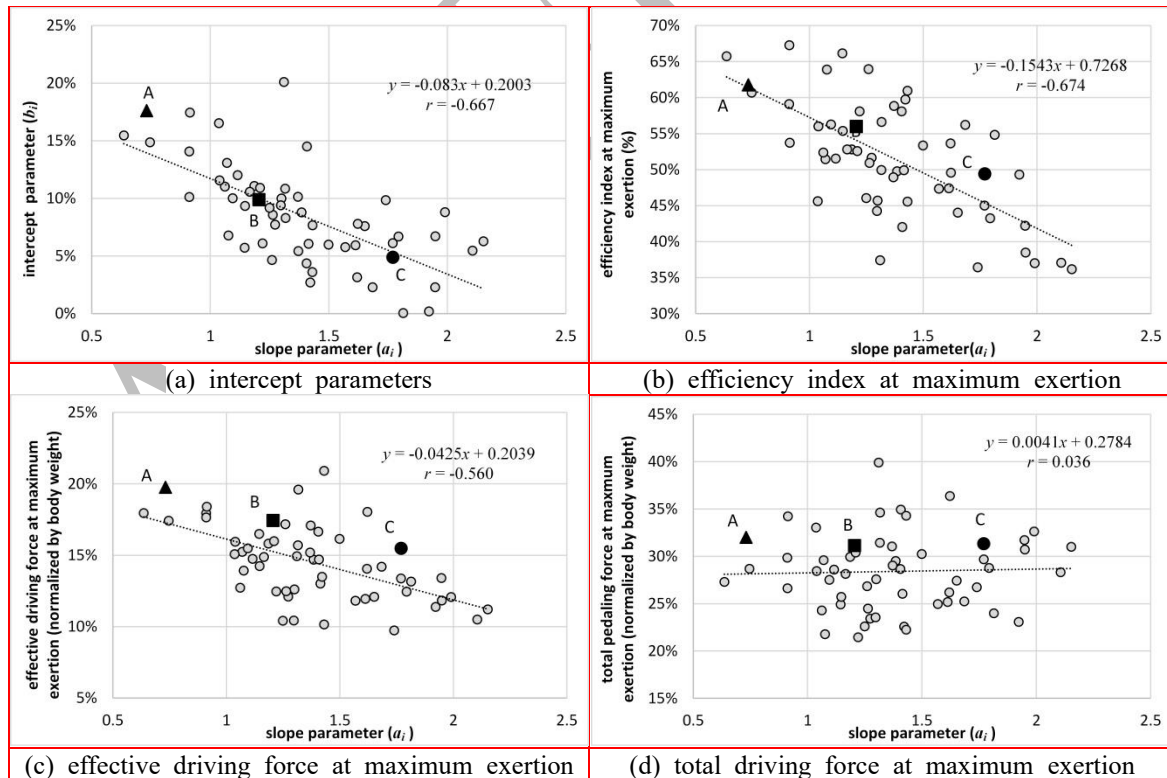


Fig. 4 Relationship between slope parameters and other measured values, (a) intercept parameters, (b) efficiency index at maximum exertion, (c) effective driving force at maximum exertion and (d) total driving force at maximum exertion

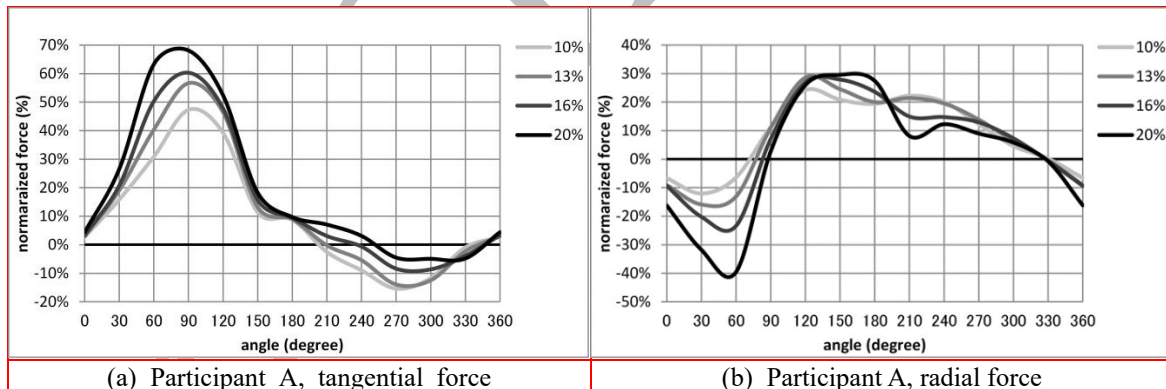
Table 3 presents the Pearson correlation coefficients calculated from these relationships. The table also presents the 95 % CI using the Fisher transformation. Consequently, we obtained good correlations of (a) -0.667, (b) -0.674, and (c) -0.560. By contrast, (d) the value was 0.036, indicating no correlation. These correlation coefficients were significantly different (a) $p < 0.0001$, (b) $p < 0.0001$, and (c) $p < 0.0001$, but not (d) $p = 0.7936$.

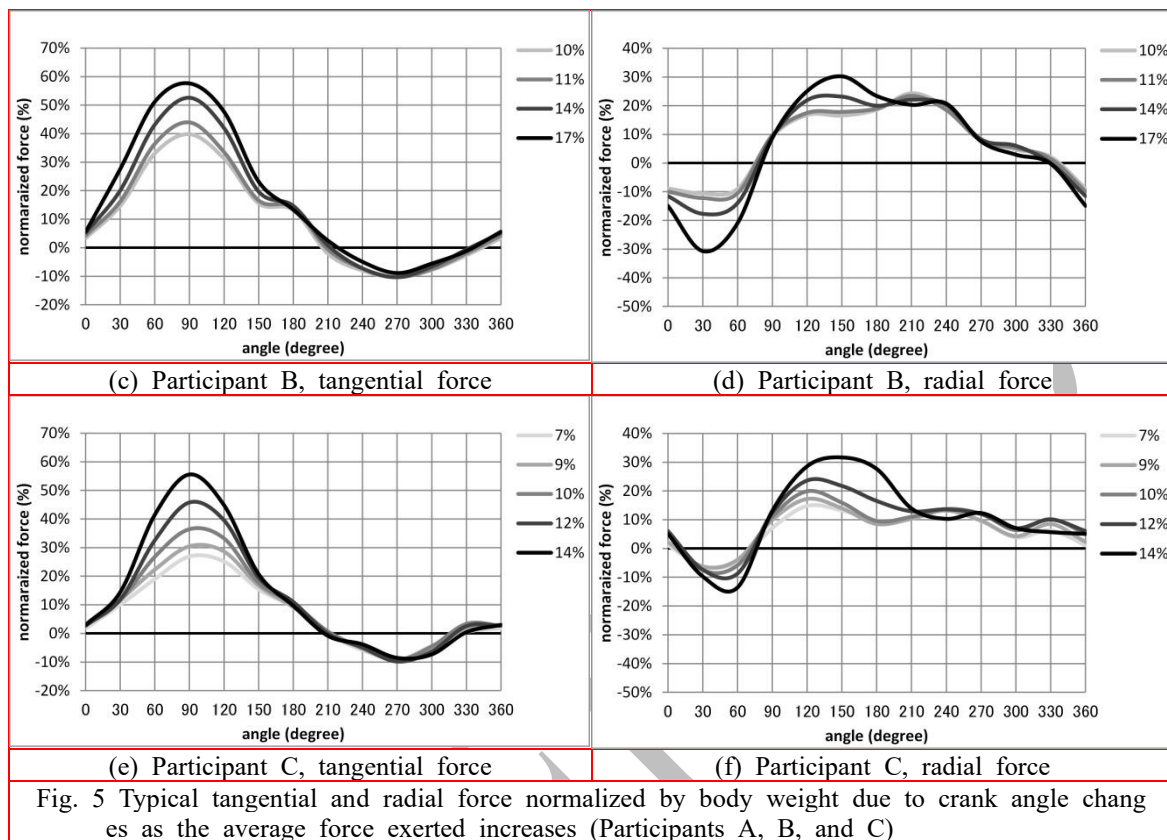
Table 3 Value of the calculated correlation coefficient with the linear regression parameter a_i

	average	95 % CI
parameter b_i	-0.667	-0.791 – -0.491
efficiency index	-0.674	-0.796 – -0.499
effective pedaling force	-0.560	-0.717 – -0.348
total pedaling force	0.036	-0.229 – 0.296

3.3 Vector data

Figure 5 shows the pedal force vector (tangential and normal directions) per body weight for each 30° rotation of the crank measured by three representative participants (A, B, and C). From this figure, each participant changed the pedaling force vector at a characteristic location, increasing the total pedaling force and average effective driving force in the tangential direction, which is the effective force.





4. Discussion

4.1 Regression data

To express the pedaling characteristics of each participant, it is better to use the relationship between the effective driving force and total pedaling force rather than using an efficiency index (Figure 3). Differences in pedaling characteristics owing to changes in load among these participants are discussed. Participant A exerted a large amount of force that did not become a propulsive force at a low-intensity load, resulting in a large total pedaling force and a low-efficiency index; conversely, at a high-intensity load that was close to 20 % of his body weight, pedaling was controlled to be more efficient. On the other hand, participant C was able to control his pedaling so that the efficiency index was large with a relatively low-intensity load of approximately 10 % of his body weight; however, he was unable to exert a high-intensity load. Participant B had characteristics between these, pedaling moderately in all load ranges and a relatively good efficiency index at an intensity of approximately 15 % of his body weight. Thus, from the relationship between the effective driving force per body weight and the total pedaling force, the load range per body weight to which each participant is adapted becomes clear, and the pedaling characteristics can be expressed well.

4.2 Regression parameter

Furthermore, Table 2(a) shows that the average correlation coefficient is 0.991, which is very

1 close to 1.0, indicating that the relationship between the effective driving force and total pedaling
2 force for each participant can be well approximated by a straight line. Furthermore, since the
3 average coefficient of determination is 0.982 and the 95 % CI is in the range of 0.9–1.0, changes in
4 total pedaling force can be fully explained by changes in effective driving force. Previous studies
5 have focused on the efficiency index [3]; however, no study has considered the relationship
6 between total pedaling force and effective driving force. This study clarified these linear
7 relationships for the first time.

8 Furthermore, Table 2(b) shows that the average value of the effective driving force normalized
9 by body weight at the maximum exertion force is 14.5 %, which is consistent with the effective
10 driving force of 14.6 % calculated from the values in Table 1 (body weight 63.3 kg, cadence 101.6
11 rpm, and maximum exertion force 325.4 W). In addition, the average value of the efficiency index
12 at maximum exertion was 51.4 %, indicating that the total pedaling force was approximately twice
13 that of the effective driving force.

14 The results in Figure 4 show that the three participants mentioned in Figure 3 exhibited the
15 characteristics of the three groups. In a group of participants with a relatively small slope
16 parameter value (1.0 or less), such as participant A, the maximum exertion force was higher in (c),
17 and the efficiency index at this time was higher in (b). Based on this, it can be assumed that they
18 acquired the pedaling skills necessary to achieve high intensity and efficiency. Furthermore, the
19 high intercept parameter in (a) indicates that the total pedaling force does not decrease
20 significantly even under low loads, which indicates that the efficiency index is low under low
21 loads. On the other hand, a group of participants with relatively large slope parameter values (1.5
22 or higher), such as participant C, had the opposite characteristics, such as pedaling characteristics
23 that maintained a high-efficiency index at low intensities in (a); however, the maximum power that
24 can be exerted is low in (c), and the efficiency index at this time is relatively low in (b).
25 Furthermore, a group of participants like participant B with an intermediate slope parameter value
26 (1.0–1.5) had a wide range of characteristics that are exactly between those of groups A and C, and
27 their maximum exertion and efficiency index at that time were intermediate. The scatter plot in (d)
28 shows that the total pedaling force per body weight at maximum exertion does not depend on the
29 slope parameter; therefore, the maximum exertion force during pedaling is independent of the
30 pedaling skill of the participant.

31 Thus, the slope parameter had a clear relationship with the pedaling skill, whereas the intercept
32 parameter did not. In another study, the force component of the action of rotating the crank without
33 any load was removed, and the force used was considered the net FE [12]. This was considered by
34 subtracting the force corresponding to the intercept parameter in this study; however, because it
35 was only measured under a single load, there was not sufficient consideration for gradually
36 increasing loads. Furthermore, this study differs from our study in that the participants were
37 limited to competitive cyclists; therefore, results from a wider range of participants were not
38 obtained. Therefore, further studies are needed to focus on the significance of the intercept
39 parameter.

40 4.3 Vector data

41 We specifically considered the pedaling characteristics of each participant based on the results
42 of the pedaling vectors (Figure 5). Participant A increased the effective driving force in the
43 tangential direction during the pushing phase and actively pulled the leg up during the recovery
44 (pulling up) phase as the load increased. Breaking down the motion of this pushing phase, the
45

1 participant applied a force diagonally forward after the pedal passed the top dead center,
2 downward when the pedal passed approximately 90°, and diagonally backwards as the pedal
3 approached the bottom dead center. Consequently, the overall effective driving force during the
4 pushing phase increases, and the pulling action during the recovery phase reduces the negative
5 force applied to the pedal. Moreover, the participant exerted approximately 70 % of his body
6 weight in a vertically downward direction when exerting maximum force. This is because, even
7 though the participant was pedaling while sitting on the saddle, he did not put much weight on the
8 saddle but instead put more weight on the pedal of one leg, similar to when he stood up, and this
9 was repeated alternately between the left and right legs. Consequently, as the load increased, the
10 efficiency index approached 70 %, and the maximum output was high.

11 However, participant C increased the load by increasing the force in the vertical downward
12 direction in the range of 60–120° during the pushing phase, and no change was observed in the
13 force vector in other regions. Moreover, from 150–180°, as the load increased, a greater downward
14 force that did not become an effective driving force was observed. With this pedaling method, the
15 efficiency index can be maintained at a relatively high value under low loads; however, the
16 effective driving force cannot be significantly increased when high loads are applied.
17 Consequently, the maximum exertion force did not increase, and the efficiency index was low.
18 Participant B was in the middle of this; his movement in the diagonally downward kicking part
19 was similar to that of participant A; however, his active leg lifting during the recovery phase was
20 small, and the increase in effective driving force was not significant; therefore, his overall
21 performance was similar to that of participant A. However, the efficiency index was not very high.

22 The efficiency index can be improved by having participants consciously pull their legs during
23 the recovery phase or by being conscious of rotation when pedaling [10] [15]. This is also
24 consistent with the fact that participant A demonstrated a high-efficiency index by utilizing the
25 pulling leg movement at a high load intensity. However, these studies required participants to force
26 their legs upward beyond their natural pedaling under certain load conditions, resulting in
27 additional movement. They concluded that although the efficiency index increases, the kinematic
28 efficiency decreases. In contrast, our results showed that by gradually increasing the leg pulling
29 motion as the load increased, the participants learned how to increase the FE according to each
30 load intensity. Therefore, the meaning of the leg-pulling motion differs from that reported by
31 previous studies.

32 Focusing on the slope parameter of the linear regression revealed the pedaling characteristics,
33 particularly the participant's ability to respond to load changes. As the load increased, the pedal
34 force vector significantly changed for each participant. Even if this pedal-force vector is not
35 available, estimating the pedaling characteristics that the participant has mastered is possible by
36 calculating the slope parameter using only the exerted power, cadence, and efficiency index.

37 38 *4.4 Features, Future, and Limitations*

39 In this study, although the linear relationship between the total pedaling force and effective
40 driving force due to a gradually increasing load has been mentioned in previous presentations [9],
41 we discovered for the first time that the slope parameter has the potential to serve as an index of
42 the characteristics of cyclist pedaling, as it is closely related to the maximum exertion force and
43 the efficiency index at that time. One of the reasons we were able to find this relationship was
44 because we used force values normalized by body weight.

45 In addition, this method is easy to implement, not only in the laboratory but also by consumers;

1 hence, the following specific methods can be considered: (1) Using the method proposed in this
2 study, the slope parameter was calculated in advance as the pedaling index of the participant using
3 a controlled load like an indoor trainer, and the pedaling characteristics were quantitatively
4 captured. (2) Using device hardware mounted on a bicycle crank, calculating the pedaling index
5 from data while riding outdoors and analyzing changes in pedaling characteristics in various
6 environments are possible. Thus, changes in pedaling characteristics can be captured in a complex
7 manner, which is expected to expand the measurement possibilities. Furthermore, by evaluating
8 the pedaling skills of participants using this pedaling index, trainers can quantitatively understand
9 pedaling skill training, which is expected to lead to more effective training and guidance.

10 In this study, we calculated the slope parameter using force values normalized by body weight
11 and considered its relationship with other values; however, calculating a similar slope parameter
12 using the torque value obtained is possible by dividing the power value by the cadence. Similarly,
13 calculating the slope parameter can be completed within the pedaling device, even without body
14 weight information; therefore, this is a more portable method. This method's ease of obtaining
15 slope parameters suggests that cyclists can widely adopt it.

16 This study had some limitations. First, the measurement load range was not sufficient in this
17 study. Notably, a wide load range is required for linear regression estimation; to increase the
18 accuracy of the linear regression estimation and the reliability of the parameters, the load range
19 should be as large as possible. Therefore, an increase in the load range from almost no load to the
20 maximum load in a short interval is recommended for more accurate measurements. Second, this
21 study was exploratory and did not adequately examine the conditions of participants, including
22 statistical pre-examination. Therefore, recruiting a wide range of participants, including
23 professional athletes and both male and female participants, is recommended for future studies to
24 ensure a statistically sufficient number of participants. Third, although a wide range of slope
25 parameters can tell us about a participant's pedaling skill, they do not tell us how improvement will
26 progress. Therefore, obtaining changes in skills by continuously measuring the indices is desirable.
27 Once the direction of improvement is clear, more effective advice can be given during training and
28 other situations.

30 5. Conclusions

31
32 Based on the results, we propose a new index for bicycle pedaling skills.

33 (1) Because the effective driving force is expressed in a linear relationship for each participant
34 with the total pedaling force during gradually increasing pedaling load, the slope of this
35 relationship will be used as the new index.

36 (2) Because the index is related to the participant's maximum pedaling force and maximum efficien-
37 cy index, and differences appear in the pedaling force vector, it could become a new index of ped-
38 aling skill.

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45 Conflicts of Interest

1
2 The author, TK, declares no conflicts of interest. The author, MF, has a contract with Shimano
3 regarding pedaling instructions, and Pioneer provided equipment.
4

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