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

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

Key words: *bicycle pedaling, pedaling force vector, force efficiency, linear regression, efficiency index*

1. Introduction

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

When considering this bicycle pedaling movement, the efficiency of how much energy the body needs to output a certain propulsive force (power value) is important. Similarly, if the participant can pedal more efficiently to achieve a specific power output, it can be considered that they have developed effective pedaling skill. There are two types of efficiency: kinematic efficiency (gross efficiency), calculated from the ratio of the total energy exerted by the body – measured from exhaled breath like VO_2max – to the propulsive force of the bicycle [4], [10], [12], [13], [16]; and mechanical efficiency index (FE), calculated from the ratio of the effective driving force to the total pedaling force [3], [6], [10], [11], [15], [21]. To measure this pedaling FE, measuring both the tangential and normal forces applied to the pedal is essential. Previously, the force

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vector acting on the pedal was measured in a laboratory. However, the force vector acting on the pedal can now be easily measured using commercially available equipment [2], [17], [18], and even ordinary cyclists can now measure the pedaling vectors and efficiency index. Thus, even when the same output load (power value) is being produced, efficiency changes depending on the pedaling motion. Therefore, the FE has been studied in relation to the muscular strength exerted [6], [21] and pedaling skill [10], [11], [15]. Because the FE is easy to measure, an objective index of the participant's pedaling motion is now routinely used. However, the FE of pedaling does not necessarily correspond to fluctuations in kinematic efficiency [10], and changes depending on the load power, cadence (number of revolutions of the crank), and body weight [3], [8]. Therefore, understanding a participant's actual pedaling characteristics and skills using the FE alone is challenging.

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

2. Methods

2.1. Participants

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

2.2. Experimental design

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

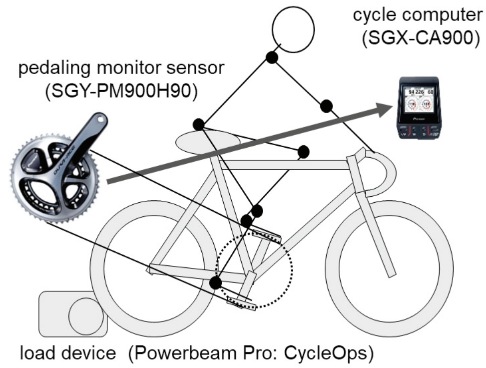


Fig. 1. Overall structure of the data recording system

In Figure 2, an example of the experimental protocol and measurement results is shown. First, the participant started pedaling with a low load intensity of approximately 150 W (equivalent to 75 W with one leg) and performed a 1-min preparatory movement to stabilize the pedaling motion. Measurements were started after 1-min had elapsed, and the load was increased by 50 W (equivalent to 25 W for one leg) every minute. After applying a sufficiently high-intensity load through a gradual increase, the measurement was terminated at the participant's discretion when the load could no longer be maintained by pedaling while sitting. The load device used in the experiment could maintain a preset constant intensity even if the cadence changed; therefore, the cadence during the experiment was set at the participant's direction.

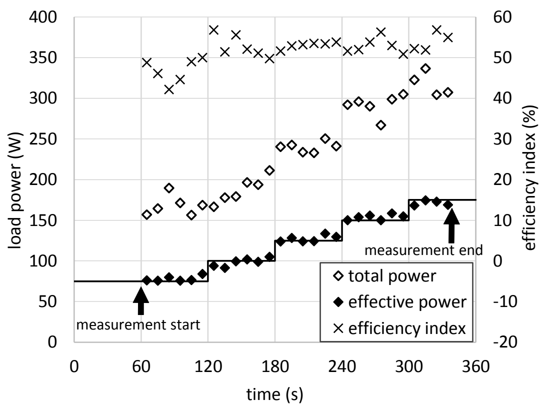


Fig. 2. Experimental protocol and example of measurement

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

The characteristics of the participants and their workloads are collected in Table 1. The load on the participants started at approximately 172 W on average and increased to approximately 329 W (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.

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

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

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

3. Results

3.1. Regression data

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

In contrast, the relationship between the effective driving force and the total pedaling force normalized by body weight (Fig. 3b) shows a linear relationship for each participant.

3.2. Regression parameter

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

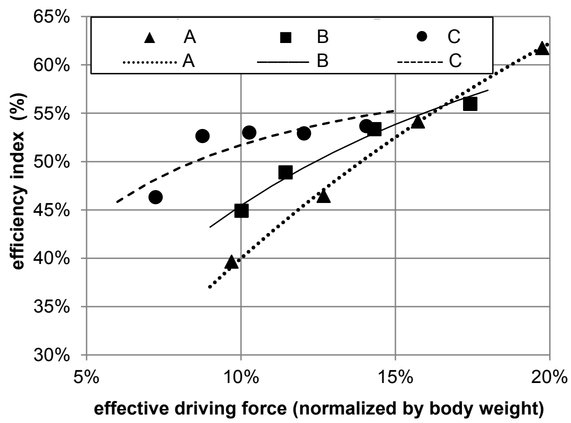
Table 2. Calculated values for evaluation of linear relationships: (a) correlation coefficient, coefficient of determination, and regression parameters

	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

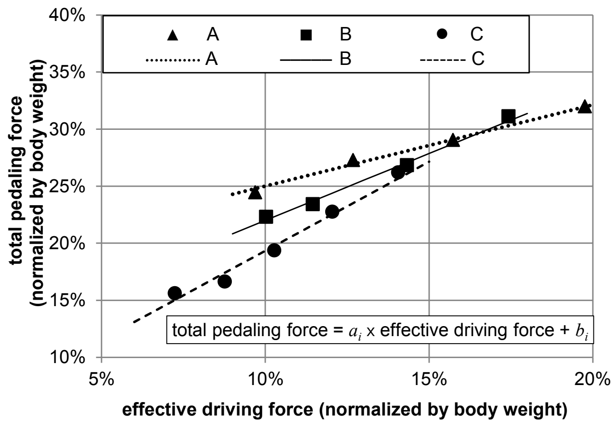
(b) measured value under maximum exertion force condition

	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,

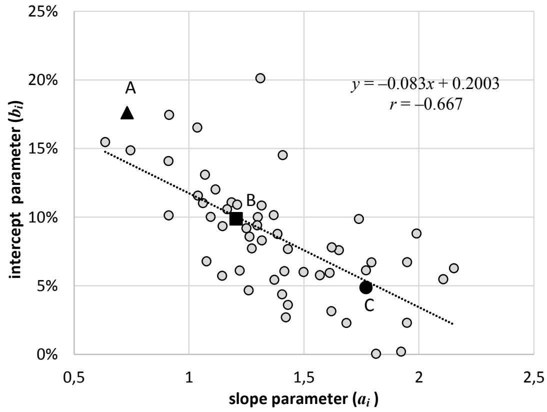


(a) Efficiency index

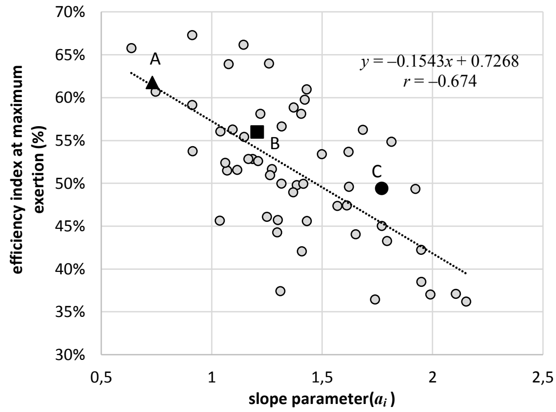


(b) Total pedaling force

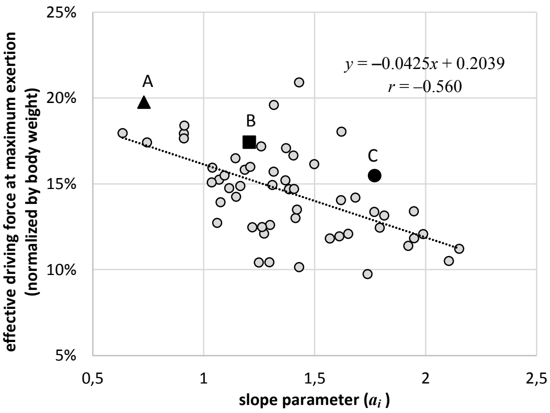
Fig. 3. Relationship between effective driving force normalized by body weight and (a) efficiency index or (b) total pedaling force for three representative participants (A, B, and C)



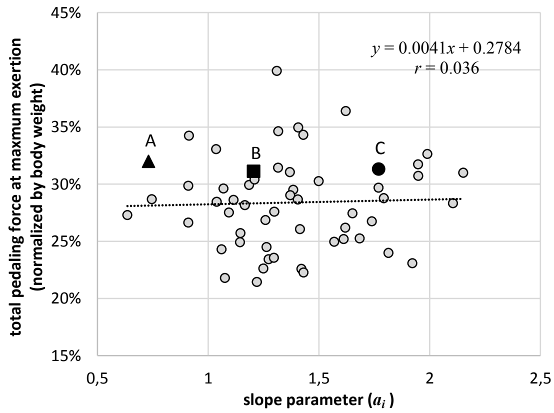
(a) Intercept parameters



(b) Efficiency index at maximum exertion



(c) Effective driving force at maximum exertion



(d) Total driving force at maximum exertion

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

(c) effective driving force at maximum exertion (%), and (d) total pedaling force at maximum exertion (%). These relationships are illustrated in Fig. 4, showing data from three participants, A, B, and C, as representative examples.

The Pearson correlation coefficients calculated from these relationships and the 95% CI using the Fisher transformation are presented in Table 3. 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

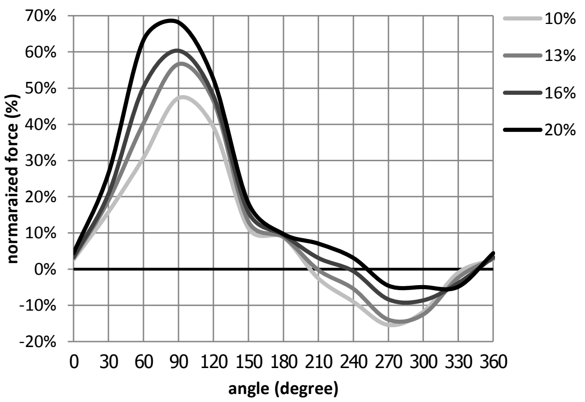
3.3. Vector data

In Figure 5, 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) is shown. Based on 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.

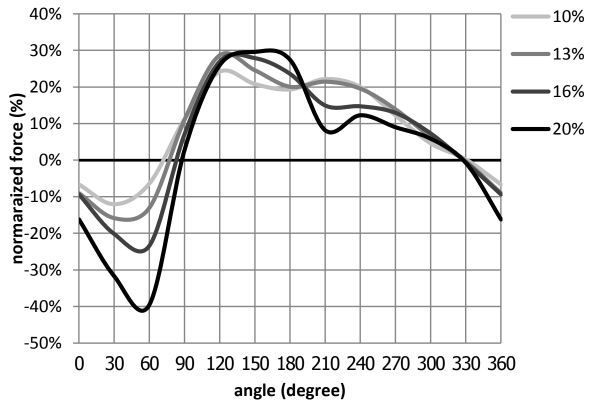
4. Discussion

4.1. Regression data

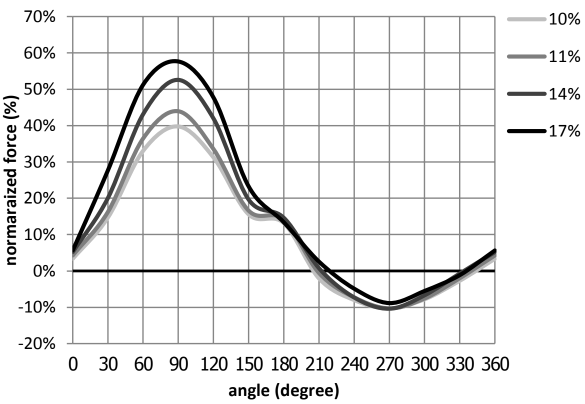
To express the pedaling characteristics of each participant, it is better to use the relationship between the effective driving force and total pedaling force



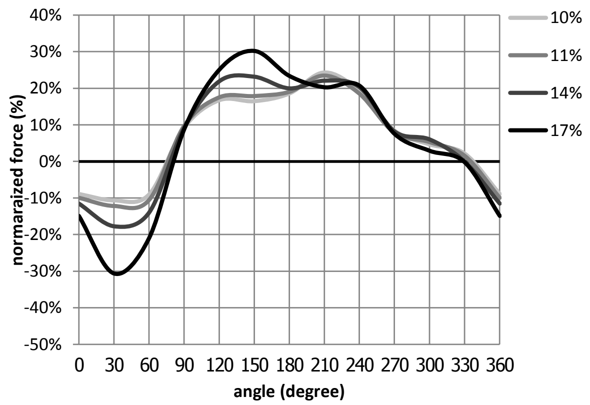
(a) Participant A, tangential force



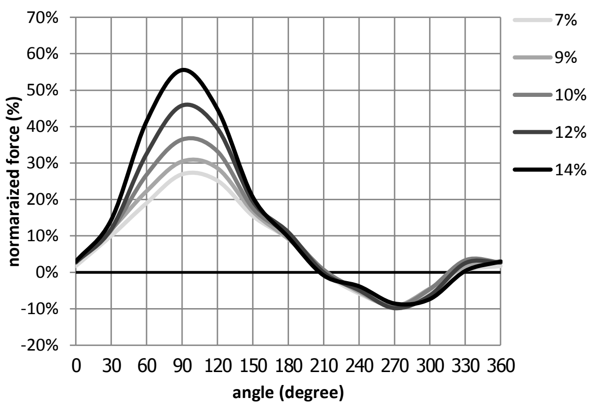
(b) Participant A, radial force



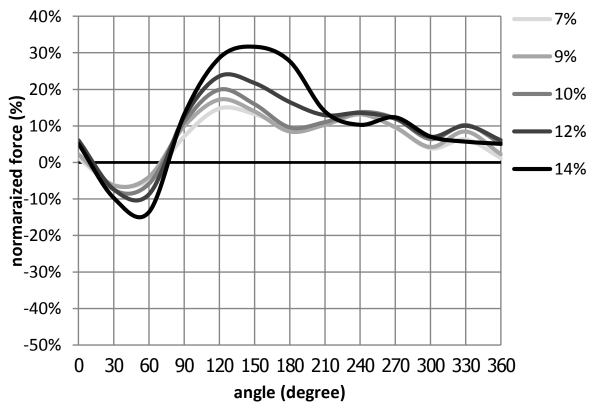
(c) Participant B, tangential force



(d) Participant B, radial force



(e) Participant C, tangential force



(f) Participant C, radial force

Fig. 5. Typical tangential and radial force normalized by body weight due to crank angle changes as the average force exerted increases (Participants A, B, and C)

rather than using an efficiency index (Fig. 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, data collected in Table 2a shows that the average correlation coefficient is 0.991, which is very close to 1.0, indicating that the relationship between the effective driving force and total pedaling force for each participant can be well approximated by a straight line. Furthermore, since the average coefficient of determination is 0.982 and the 95% CI is in the range of 0.9–1.0, changes in total pedaling force can be fully explained by changes in effective driving force. Previous studies have focused on the efficiency index [3]; however, no study has considered the relationship between total pedaling force and effective driving force. This study clarified these linear relationships for the first time.

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

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

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

4.3. Vector data

We specifically considered the pedaling characteristics of each participant based on the results of the pedaling vectors (Fig. 5). Participant A increased the effective driving force in the tangential direction during the pushing phase and actively pulled the leg up during the recovery (pulling up) phase as the load increased. Breaking down the motion of this pushing phase, the participant applied a force diagonally forward after the pedal passed the top dead center, downward when the pedal passed approximately 90°, and diagonally backwards as the pedal approached the bottom dead center. Consequently, the overall effective driving force during the pushing phase increases, and the pulling action during the recovery phase reduces the negative force applied to the pedal. Moreover, the participant exerted approximately 70% of his body weight in a vertically downward direction when exerting maximum force. This is because, even though the participant was pedaling while sitting on the saddle, he did not put much weight on the saddle but instead put more weight on the pedal of one leg, similar to when he stood up, and this was repeated alternately between the left and right legs. Consequently, as the load increased, the efficiency index approached 70%, and the maximum output was high.

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

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

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

4.4. Features, future, and limitations

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

In addition, this method is easy to implement, not only in the laboratory but also by consumers; hence, the following specific methods can be considered: (1) Using the method proposed in this study, the slope parameter was calculated in advance as the pedaling index of the participant using a controlled load like an indoor trainer, and the pedaling characteristics were quantitatively captured. (2) Using device hardware mounted on a bicycle crank, calculating the pedaling index from data while riding outdoors and analyzing changes in pedaling characteristics in various environments are possible. Thus, changes in pedaling characteristics can be captured in a complex manner, which is expected to expand the measurement possibilities. Furthermore, by evaluating the pedaling skills of participants using this pedaling index, trainers can quantitatively understand pedaling skill training, which is expected to lead to more effective training and guidance.

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

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

5. Conclusions

Based on the results, we propose a new index for bicycle pedaling skills, first because the effective driving force is expressed in a linear relationship for each participant with the total pedaling force during gradually increasing pedaling load, the slope of this relationship will be used as the new index, the second because the index is related to the participant's maximum pedaling force and maximum efficiency index, and differences appear in the pedaling force vector, it could become a new index of pedaling skill.

Conflicts of interest

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

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References

[1] BIEUZEN F., LEPERS R., VERCRUYSSEN F., HAUSSWIRTH C., BRISSWALTER J., *Muscle activation during cycling at different cadences effect of maximal strength capacity*, J. Electromyogr. Kinesiol., 2007, 17 (6), 731–738, https://doi/10.1016/j.jelekin.2006.07.007.

[2] Bikefitting.com B.V., https://bikefitting.com/en/ [Accessed: 8 Nov. 2024].

[3] BINI R.R., HUME P.A., CROFT J., KILDING A.E., *Pedal force effectiveness in Cycling: a review of constraints and training effects*, J. Sc. Cycling, 2013, 2 (1), 11–24.

[4] CÁMARA J., MALDONADO-MARTÍN S., ARTETXE-GEZURAGA X., VANICEK N.I., *Infuence of pedaling technique on metabolic efficiency in elite cyclists*, Biol. Sport, 2012, 29 (3), 229–233, https://doi/10.5604/20831862.1003448

[5] CHAPMAN A.R., VICENZINO B., BLANCH P., HODGES P.W., *Patterns of leg muscle recruitment vary between novice and highly trained cyclists*, J. Electromyogr. Kinesiol., 2008, 18 (3), 359–371, https://doi/ 10.1016/j.jelekin.2005.12.007

[6] DOREL S., DROUET J.M., COUTURIER A., CHAMPOUX Y., HUG F., *Changes of pedaling technique and muscle coordination during an exhaustive exercise*, Med. Sci. Sports Exerc., 2009, 41 (6), 1277–1286, https://doi/10.1249/MSS.0b013e31819825f8

[7] GREGERSEN C.S., HULL M.L., HAKANSSON N.A., *How changing the inversion/eversion foot angle affects the nondriving intersegmental knee moments and the relative activation of the vastii muscles in cycling*, J. Biomech. Eng., 2006, 128 (3), 391–398, https://doi/10.1115/1.2193543

[8] KITAWAKI T., TOKUYASU T., OKA H., *Efficiency index of a pedaling monitor system depend on load power, cadence and body weight*, J. Sci. Cycling, 2014, 3 (2), 25.

[9] KITAWAKI T., FUKUDA M., *Relationship between effective driving force and total pedaling force during bicycle pedaling varying with increasing load*, Appl. Physiol. Nutr. Metab., 2023, 48, S146, https://doi.org/10.1139/apnm-2023-0378

[10] KORFF T., ROMER L.M., MAYHEW I., MARTIN J.C., *Effect of pedaling technique on mechanical effectiveness and efficiency in cyclists*, Med. Sci. Sports Exerc., 2007, 39 (6), 991–995, https://doi/10.1249/mss.0b013e318043a235

[11] KORFF T., FLETCHER G., BROWN D., ROMER L.M., *Effect of "Pose" cycling on efficiency and pedaling mechanics*, Eur. J. Appl. Physiol., 2011, 111 (6), 1177–1186, https://doi/10.1007/s00421-010-1745-7

[12] LEIRDAL S., ETTEMA G., *Pedaling technique and energy cost in cycling*, Med. Sci. Sports Exerc., 2011, 43 (4), 701–705, https://doi/10.1249/MSS.0b013e3181f6b7ea

[13] LUCIA A., SAN JUAN A.F., MONTILLA M., CANETE S., SANTALLA A., EARNEST C., PÉREZ M., *In professional road cyclists, low pedaling cadences are less efficient*, Med. Sci. Sports Exerc., 2004, 36 (6), 1048–1054, https://doi.org/10.1249/01.mss.0000128249.10305.8a

[14] MORNIEUX G., ZAMEZIATI K., MUTTER E., BONNEFOY R., BELLI A., *A cycle ergometer mounted on a standard force platform for three-dimensional pedal forces measurement during cycling*, J. Biomech., 2006, 39 (7), 1296–1303, https://doi.org/10.1016/j.jbiomech.2005.03.020

[15] MORNIEUX G., STAPELFELDT B., GOLLHOFER A., BELLI A., *Effects of pedal type and pull-up action during cycling*, Int. J. Sports Med., 2008, 29 (10), 817–822, https://doi.org/10.1055/s-2008-1038374

[16] MOSELEY L., ACHTEN J., MARTIN J.C., JEUKENDRUP A.E., *No differences in cycling efficiency between world-class and recreational cyclists*, Int. J. Sports Med., 2004, 25 (5), 374–379, https://doi.org/10.1055/s-2004-815848

[17] Pioneer: pedaling monitor system, https://www.pioneer.com.au/product-category/cycle-sports/power-meters/ [Accessed 8 Nov. 2024].

[18] Shimano: Power Meter Technology, https://bike.shimano.com/technologies/details/power-meter-technology.html [Accessed: 8 Nov. 2024].

[19] STAPELFELDT B., MORNIEUX G., OBERHEIM R., BELLI A., GOLLHOFER A., *Development and evaluation of a new bicycle instrument for measurements of pedal forces and power output in cycling*, Int. J. Sports Med., 2007, 28 (4), 326–332, https://doi.org/10.1055/s-2006-924352

[20] TRUMBOWER R.D., FAGHRI P.D., *Improving pedal power during semireclined leg cycling*, IEEE Eng. Med. Biol. Mag., 2004, 23 (2), 62–71, https://doi.org/10.1109/memb.2004.1310977

[21] ZAMEZIATI K., MORNIEUX G., ROUFFET D., BELLI A., *Relationship between the increase of effectiveness indexes and the increase of muscular efficiency with cycling power*, Eur. J. Appl. Physiol., 2006, 96 (3), 274–281, https://doi.org/10.1007/s00421-005-0077-5